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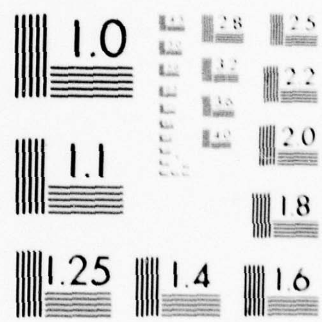

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A REPORT ON ATMOSPHERIC OBSTRUCTIONS TO VISIBILITY

Volume I - Study Results

(6)

RAMCOR INC.

LEVEL II

Prepared by: Victor J. Lujetic

10 March 1979

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Final Report

Prepared for

U.S. Army Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060

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Contrast	Scattering	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The aims and objectives of this report were to collect and assimilate information and synthesize data on the effects of atmospheric obstructions to visibility for the non-specialist. The following areas were addressed:

- A general discussion of the visible wavelengths, overall electromagnetic spectrum, radiometric and photometric quantities and concepts, and other visibility parameters;
- The human eye, nature of visibility, and the atmospheric effects on detection ranges;
- A description of those obstructions to visibility as listed in the Federal Meteorological Handbook on surface observations;
- A description of the primary visual instruments;
- The practicality of developing techniques that could be used to determine the effects of atmospheric obstructions on visibility and some typical charts and graphs; and
- A summary of the extensive literature search performed.

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PREFACE

This study on the atmospheric effects on visibility was performed to satisfy the requirements of government contract DAAK70-78-C-0109. This final technical report consists of two volumes:

- Volume I - Study Results, and
- Volume II - Results of Literature Search.

These two volumes are submitted per Item A002 of the Contract Data Requirements List and constitute the final technical deliverable for this contract. The Contractor Office Representative (COR) was Dr. Llewelyn Williams.

The study was oriented to the non-specialist and addressed the five required tasks of the contract. The report covered the following areas in order to achieve the aims and objectives of the study effort (where the sections apply to Volume I):

- Section 0 - Summary
- Section 1 - Nature of Light
- Section 2 - Visual Detection
- Section 3 - Obstructions to Visibility
- Section 4 - Instruments for Measurement of Visual Range
- Section 5 - Techniques for Determining Visibility
- Section 6 - List of Definitions
- Volume II - Results of Literature Search

The study findings resulted in the principal conclusion that it would be practical to develop charts and graphs that could be used to determine specific measurements of the effects of atmospheric obstructions on different types of observations and ranging devices. To illustrate this, some typical charts and graphs are included. The study also includes other conclusions and the principal recommendation that the methods presented in this study effort be refined, expanded and applied to specific situations.

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0. SUMMARY

INTRODUCTION

This study on the atmospheric effects on visibility was performed to satisfy the requirements of government contract DAAK70-78-C-0109. This final technical report consists of two volumes:

- Volume I - Study Results, and
- Volume II - Results of Literature Search.

These two volumes are submitted per Item A002 of the Contract Data Requirements List and constitute the final technical deliverable for this contract.

Contract Requirements

The contract requirements and the aims and objectives of this report on atmospheric obstructions to visibility were to collect and assimilate information and synthesize data for a report written for the non-specialist covering the following:

- Task 1. A general discussion of the visible wavelengths and their attenuation by the reported obstructions to visibility as listed in the Federal Meteorological Handbook on Surface Observations and other effects on visibility.
- Task 2. Summary of current efforts in probing the meteorological conditions of the lowest 300-400 feet of the atmosphere.
- Task 3. Abstracts of reports in open literature on the effects of atmospheric obstructions to visibility.
- Task 4. A conclusion as to whether it would be practical to develop charts and graphs that could be used to determine specific measurements of the effects of atmospheric obstructions on different types of observations and ranging devices.
- Task 5. If the conclusion is positive, recommendations as to methods for constructing such charts and graphs.

Study Approach and Structure of Report

The study approach was oriented to addressing the five tasks listed above in such a manner as to develop a comprehensive and complete report that covers the atmospheric obstructions to visibility from an extensive literature research through the practicality of developing methods for displaying these effects. The study results were oriented to the non-specialist in addressing atmospheric obstructions to visibility. The report contents are structured in the following manner to achieve the aims and objectives of the study effort (where the sections apply to volume I):

- Section 0 - Summary. This section covers the contractual requirements, report structure, conclusions, and recommendations.

- Section 1 - Nature of Light. This section addresses Tasks 1 and 3 and presents a general discussion of the visible wavelengths, the overall electromagnetic spectrum, and the radiometric and photometric quantities and concepts. Finally, reflectance, contrast, and atmospheric attenuation are covered along with a brief discussion of the effects of turbulence and thermal stratification.

- Section 2 - Visual Detection. This section addresses Tasks 1, 2 and 3 and covers the human eye, the nature of visibility, and the atmospheric effects on detection ranges. An approach for determining the visual detection of objects, the maximum range at which a target can be seen, and the chance that the target will be seen while at any given range, is discussed and developed. Most of the basic expressions that are used in later sections of the report are developed in this section. This includes the basic expressions for object contrast, visual range on objects, meteorological range, standard daytime and nighttime visual ranges, and visual range on lights.

- Section 3 - Obstructions to Visibility. This section addresses Tasks 1, 2, and 4 and describes those obstructions to visibility as listed in the Federal Meteorological Handbook on Surface Observations. Typical effects on visibility by atmospheric obstructions are covered in the form of visibility ranges versus intensity of the obstructions. A set of visibility states were formulated and the meteorological ranges for different weather conditions and attenuation coefficients were summarized. Finally, the effects of these atmospheric obstructions on the attenuation coefficient is presented as representative of the types of data and information that are required and useful in assessing the effects of atmospheric obstructions in the visual and outside the visual frequency spectra.

- Section 4 - Instruments for Measurement of Visual Range. This section addressed Tasks 1 and 2 and discusses the primary visual instruments, including telephotometers, transmissometers, and scattering coefficient meters. In particular, the transmissometer is described and the transmissivity and other related expressions are developed.

- Section 5 - Techniques for Determining Visibility. This section addresses Tasks 4 and 5 and the practicality of developing techniques, such as charts and graphs, that could be used to determine the visibility due to the effects of atmospheric obstructions on different types of observations and ranging devices. In addition, the section covers the basic visibility equations and typical charts and graphs that could be used.

- Volume II - Results of Literature Search. This volume addresses Tasks 2 and 3 and contains the results of the extensive literature search performed in the form of publications and abstracts of reports on the atmospheric effects on visibility selected for the non-specialist.

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

As a result of this study and analysis, the following findings and conclusions are presented:

- The principal conclusion is that it would be practical to develop charts and graphs that could be used to determine specific measurements of the effects of atmospheric obstructions on different types of observations and ranging devices. Some typical charts and graphs are included in section 5 and illustrate the methods that could be employed to determine the visibility for a variety of conditions. These charts and graphs use the visibility equations and atmospheric obstruction effects on visibility that were developed during this study effort. It is also concluded that other types of charts and graphs could be developed such as scattergrams which relate the visibilities of observers with instruments using measurement data. The development of charts and graphs relating ranges for observations in the visible spectrum to those outside the visible spectrum are possible only if a viable set of relationships can be determined and relied on, such as that included in section 3. These relationships essentially cover the attenuation coefficient and other parameters over an appropriate frequency spectra.

- Visibility is one of the most complicated of all meteorological elements. The measure of visibility and visual range depends on the characteristics of the atmosphere, the type of viewing instrument, the type of object or light being detected, and the manner by which the object or light is being viewed. The primary factors influencing visibility include:

  -- reflecting power and color of the object,

  -- reflecting power of the background,

  -- amount of scattering and absorbing particles,

  -- position of the sun,

  -- angular size of the object,

  -- nature of the terrain between the object and observer,

  -- contrast of the object, and

  -- intensity of the light source.

- The visibility on objects and lights can be summarized in the following set of equations:

$V = \frac{1}{\beta} \ln \frac{C_o}{C_t}$	day visibility	(0-1)
$\frac{I}{E} = \frac{1}{V^2} e^{-\beta V}$	visibility on lights	(0-2)
$C_t = e^{-\beta V} = T^V$	contrast threshold	(0-3)
$T = e^{-\beta}$	transmissivity	(0-4)
$\beta = -\ln T$	attenuation coefficient	(0-5)
$V_M = \frac{-\ln C_t}{\beta}$	meteorological visibility	(0-6)
$V_M = \frac{3.912}{\beta} \quad (C_t = 0.02)$	meteorological visibility	(0-7)
$T^{V_M} = 0.02 \quad (C_t = 0.02)$	meteorological visibility	(0-8)
$T^{V_d} = 0.05 \quad (C_t = 0.05)$	day visibility	(0-9)
$\frac{T^{V_N}}{V_N} = 0.0034$	night visibility on lights	(0-10)

- The basic attenuation mechanisms are scattering and absorption and they have a twofold effect on the propagation of light from an object to an observer. First, light coming from an object of interest and from its background is progressively removed from the viewing path and does not reach the observer and, second, light which has not come directly from the object or from its immediate background is scattered into the viewing path.

  -- scattering is the process by which a particle, any bit of matter, in the path of an electromagnetic wave continuously abstracts energy from the path incident wave and reradiates that energy. The three types of scattering are (1) Rayleigh scattering that occurs when the particle is far smaller than the wavelength of light, (2) Mie scattering that occurs when the particles range from roughly 1/10 to 10 wavelengths (Figure 1-1 illustrates the unit of wavelength) in size, and (3) Nonselective scattering that occurs when the particles are larger than about 10 wavelengths.

-- Absorption is the process by which agents in the atmosphere abstract energy from a light wave. These absorbing agents are mainly water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), ozone (O_3), molecular and atomic oxygen (O,O_2), and molecular and atomic nitrogen (N,N_2). In the infrared there are discrete absorption bands, while in the ultra-violet the transmission at wavelengths below 0.3 microns is very low. In the visible region, there is little absorption on a clear day, and it is generally negligible when the water content is low. For the visible wavelengths, roughly 0.38 to 0.76 microns, nearly all the absorption is because of the water vapor in the atmosphere. In the infrared region the absorption results from the presence of water vapor, carbon dioxite, nitrous oxide, and ozone. In the ultraviolet everything absorbs at some wavelengths. From 0.22 to 0.13 microns, the absorption is due to ozone. It should be pointed out that ozone is not present in the lower atmosphere where this atmospheric visibility report is being addressed. Below 0.13 microns, the absorption is caused mainly by atomic and molecular nitrogen and oxygen. The situation is rather different in regions where the atmosphere is polluted with industrial waste. A suspension of black soot particles is a strong absorber. In fact, with such atmospheres, absorption has been found to be very dependent on the particular conditions, both in magnitude and spectral properties.

- There are a number of theories and models that have been exercised in attempting to determine the attenuation coefficients for particles in the atmosphere. These are covered in section 3 and indicate good correlation between measured and theoretical values of the attenuation coefficients over a broad range of wavelengths. There appears to be some useful data and information that could be used to predict these values based on the atmospheric conditions.

- Most sensors are sensitive beyond the limits of the visible spectrum and within the visible spectrum sensitivity often differs from that of the eye. Moreover, the response of the human eye is not constant. It varies among individuals, with the level of illumination, and other factors. However, the human eye is still considered to be the best visual instrument for detecting objects and lights.

- There are a number of instruments that have been developed and used for the measurement of visual range. These instruments can be separated into two categories.

  -- Those that determine the transmittance of a path of known length using a light source and a telephotometer. Transmissometers are instruments of this type.

-- Those that measure the scattered light directly by sampling a small volume of air using a source and a receiver. Backscatter, side-scatter, and forward-scatter meters are examples of these type of instruments.

- The primary atmospheric obstructions to visibility were obtained from the Federal Meteorological Handbook on surface observations and are fog, ground fog, ice fog, haze, smoke, dust, blowing snow, blowing sand, blowing dust, and blowing spray. The effects of these atmospheric obstructions on visibility depends on their intensities. The visibility states and meteorological ranges depend on the different weather conditions and attenuation coefficients. These are summarized in section 3.

The principal recommendation, following the conclusion that charts and graphs can be developed, is that the methods presented in this study effort be refined, expanded, and applied to specific situations for the non-specialist. As a result, it is recommended that this effort be continued by utilizing the results of this study to refine and expand on the charts and graphs of section 5.

1. NATURE OF LIGHT

LIGHT

The subject of light (optical radiation) as a form of radiant energy has been theorized upon, experimented with, and studied by many renowned physicists, philosophers, and scientists down through the centuries. Until about 300 years ago, no one had developed a reasonable theory of the nature of light. Then, Sir Isaac Newton published his corpuscular theory in which light was supposed to consist of a stream of high speed particles. Newton believed that any source of light sent out an untold number of these particles.

About the same time, physicist Christian Huygens introduced an entirely new wave motion theory of light. Huygens believed that light consisted of a series of small waves which, upon entering the human eye, produced sight. The major unknown associated with this theory was the manner in which light waves traveled from the sun to the surface of the earth through empty space. Waves require some medium in which to travel. Thus, a new substance called ether was presumed to exist in all outer space and was credited with affording such a medium.

Further scientific study conducted in the 1800's by Thomas Young and Augustin Fresnel on the interference of light materially substantiated Huygens' wave theory. The physical nature of the light waves presented in Huygens' theory was the source of much debate during the 19th century. It was not until 1873 that Maxwell and Hertz conducted a series of experiments that seemed to prove that light was wave motion. These experiments resulted in the introduction of Maxwell's electromagnetic theory of light. However, this latter theory could not explain certain aspects of the photoelectric effects, nor could it explain the spectral distribution in the radiation of a heated body.

In 1900, in an effort to explain some of these problems, Max Planck began experimenting with the photoelectric effect. He assumed that the light energy does not travel in a steady flow like waves but in little packages or particles. He called these particles quanta, and his theory became known as the quantum theory. The Planck theory was supported by Einstein, whose mathematical equations proved that quanta somehow possessed a frequency like that of waves, but existing in the form of particles. By 1921, Einstein's equations proved correct when it was found that particles of light have momentum and kinetic energy as do particles of matter. These facts came to light during the study of the motion of the electron and the light quantum conducted by R. A. Millikan and A. H. Compton.

At the present time, the wave motion theory (used to explain reflection,* interference, refraction, diffraction, and polarization) and the quantum theory (used to explain x-rays, radiation, and photoelectricity) exist side by side as accepted scientific explanations of the nature of light. As a result, from a classical point of view, light displays the following two seemingly contradictory properties,

- propagates through space as waves, and

- possesses a definite particulate nature, since a discrete energy and momentum are associated with them.

Each of these properties is important to the complete understanding of the behavior of all electromagnetic radiations. Both properties are combined in the current concept of light as described by quantum mechanics.

Electromagnetic Waves

Maxwell's wave theory states that light and similar forms of radiation are believed to be transmitted through the medium known as ether in the form of wave motion, and that these waves are characterized by moving electrical and magnetic forces. Most forms of radiant energy occur as electromagnetic waves in which vibrations are transverse or perpendicular to the direction of propagation of the wave. Figure 1-1 represents a single electromagnetic wave, such as that of light. The horizontal arrow represents the direction of propagation while the vertical arrow represents the displacement of a particle due to wave motion. The amplitude of a wave is the maximum displacement from the AB axis.

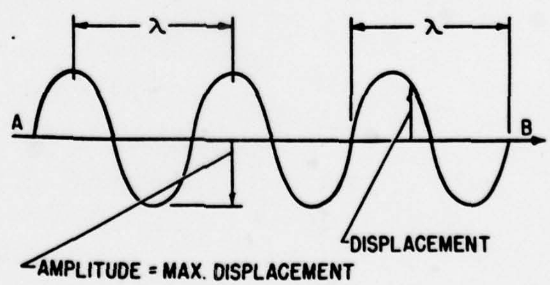


FIGURE 1-1. SIMPLE FORM OF WAVE MOTION.

*Definitions of terms are summarized in section 6 of this report.

Since electromagnetic radiations are thought of as wave motion, it follows that there must be a specific wavelength (λ) associated with any given radiation. A wavelength is represented by the distance between successive corresponding points in one vibration of the electromagnetic wave. It is measured from any point moving in the same direction and having the same displacement from the zero axis as shown by λ in Figure 1-1.

In the air or in a vacuum, light travels about 3×10^8 meters per second. It travels more slowly in a denser medium such as glass. The determination of the velocity of electromagnetic waves is dependent upon the medium through which waves travel. Velocity will vary with the nature of this medium and the wavelength of the radiation. If one wishes to actually measure a wavelength in any wave motion, simply allow v to represent the velocity of the wave and T to represent the time for one wave to pass a fixed point. Then,

$$\lambda = vT, \qquad (1\text{-}1)$$

where,

λ = wavelength in meters,

v = velocity of the wave in meters/second, and

T = period or time for one wave to pass a fixed point in seconds.

Substituting the reciprocal of T and the speed of light in a vacuum for v results in the following basic expression for the wavelength:

$$\lambda = c/f, \qquad (1\text{-}2)$$

where,

c = speed of light in a vacuum in meters/second, and

f = frequency of light waves in cycles/second or **Hertz** (Hz)

Light Compared to Sound

In many respects the waves which produce light can be compared to sound waves. Vibrations in the air cause sound waves which produce the sensation of sound when they reach the human ear. In the same manner, a luminous light source acts as an oscillator which causes a disturbance in the space around it, generating light waves that spread in all directions, much as the vibrating string of a guitar produces the air waves that are called sound. For example, oscillating atoms in the glowing filament of an electric lamp radiate energy in the form of light waves which produce the sensation of sight when they reach the eyes. Both sound and light waves radiate in all directions from their sources and become weaker as they travel farther from the sources.

Sound waves vary in length, and human ears are capable of registering only a part of them as sound. Long air waves cannot be heard, but as they are gradually shortened, the ear can begin to hear the deep bass tones. Further shortening of the air waves register as higher tones, through the middle register to the high pitched tones, where further shortening of the waves places them outside the hearing zone on the opposite side from the start. So it is with light. Comparatively long light waves do not affect the eyes. As the waves gradually shorten, the eyes will begin to perceive the deepest reds. Further shortening of these waves leads through the remainder of Newton's seven spectral colors; orange, yellow, green, blue, indigo, and violet. Finally, these waves become so short that they have no effect on the eyes and are invisible.

Very few sounds are caused by vibrations on only one wavelength in the air, but by a combination of several wavelengths which make up that sound. The same is true of light. Very few colors are produced by only one light wavelength. Combinations of various wavelengths register as various colors as seen by the eyes. It is interesting to note, however, that each different wavelength of light produces its own characteristic color.

Electromagnetic Spectrum

As a form of electromagnetic energy, light occupies that portion of the electromagnetic spectrum with which man first dealt because it was visible to the human eye. Originally, the term light included only the visible frequencies. About 1800, the British-German astronomer W. Herschel placed a thermometer just beyond the blue portion of a spectrum produced by a prism using sunlight and found its temperature was raised. Later, invisible light was found on the other side of the visible spectrum. Thus frequencies outside the visible range were lumped with the visible frequencies under the term light or optical radiation. When x-rays, radio waves and other discoveries were made, light was found to be part of a spectrum of electromagnetic radiations. The primary distinction among the various radiations is energy which is proportional to the frequency or wavelength of the radiation and is expressed as follows,

$$P = hf = hc/\lambda \qquad (1\text{-}3)$$

where, P = energy in joules,

h = Planck's constant in joules/second,

f = frequency in cycles/second or Hz,

c = velocity of light in meters/second, and

λ = wavelength in meters.

The electromagnetic spectrum may be divided into nine major regions of radiation depending on the generation character of the waves:

- long electric waves,
- radio waves,
- radar,
- infrared,
- visible light,
- ultra-violet,
- x-rays,
- Gamma rays, and
- cosmic rays.

Together, all of these form the electromagnetic spectrum, illustrated in Figure 1-2 and show that the wavelengths of light are between 0.4 and 0.7 microns and each spectral color has its own small range of wavelengths. For example, if light around 0.66 microns of wavelengths reaches your eyes, you see red because of the sensation of red on the retina of the human eye. Around 0.46 microns, the wavelengths of light which reach your eyes are blue so the red waves are much longer than the blue waves. When light with wavelengths outside the visible spectrum reach the eyes, there is no sensation of color and these are outside the visible spectrum.

In studying light perhaps the most confusing aspect to both the specialist and non-specialist is the inconsistent manner in which one refers to light radiation. As already noted, the major distinction among the various electro-magnetic radiations is energy which is proportional to frequency which in turn is proportional to wavelength. Thus one can describe a specific light radiation in a variety of ways. To simplify the manner by which these parameters can be expressed, the simple nomograph of Figure 1-3 can be used for easy conversion among these units.

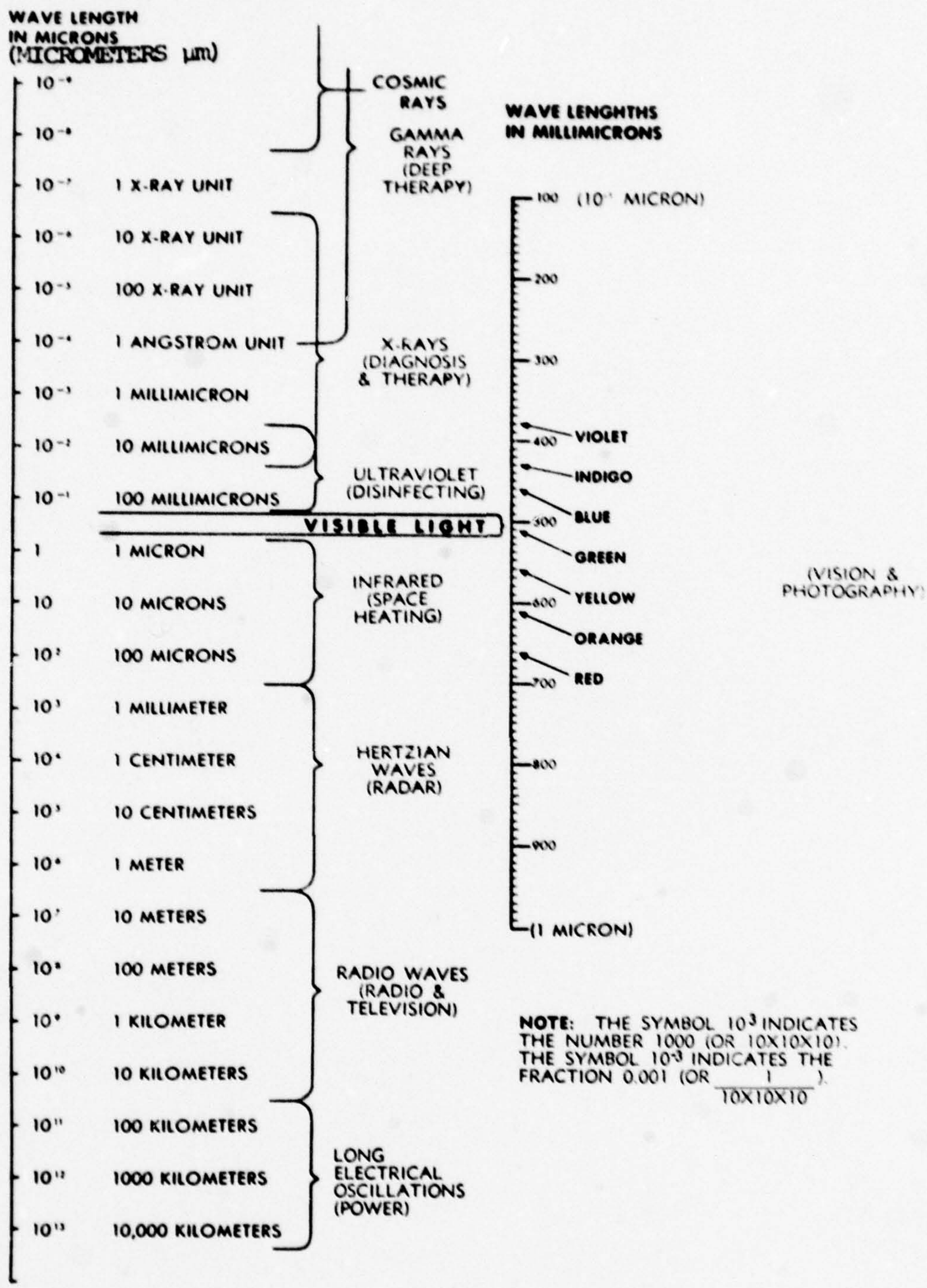
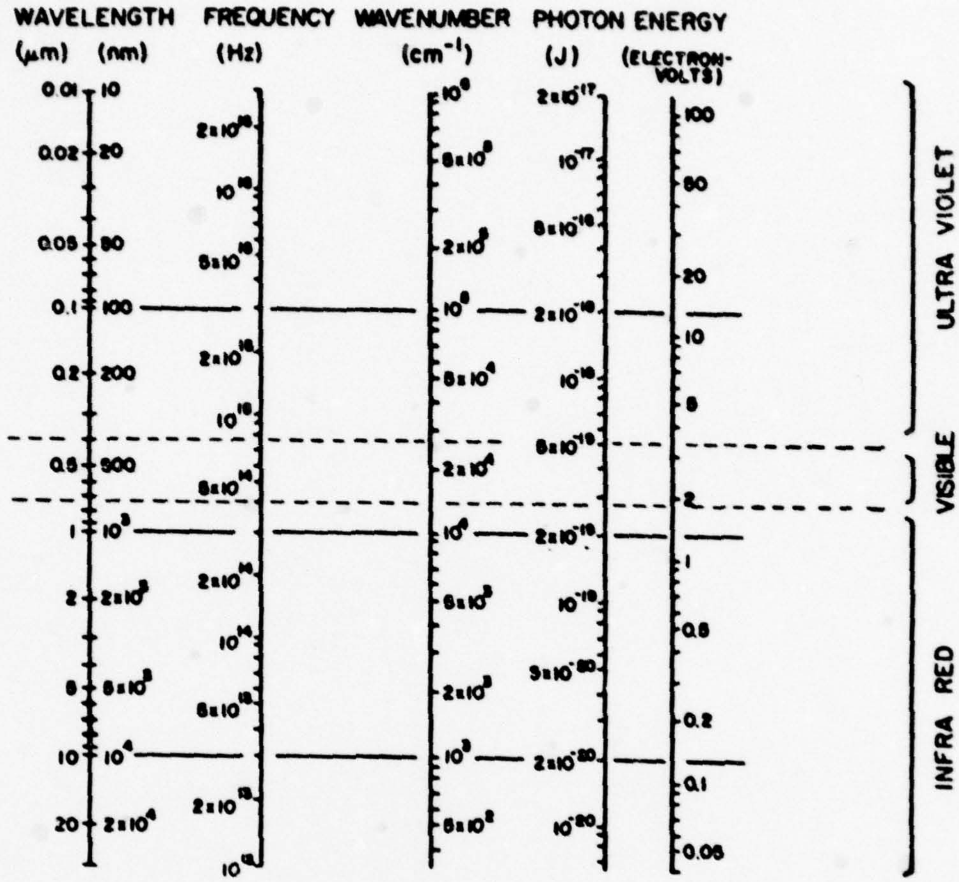


FIGURE 1-2. ELECTROMAGNETIC SPECTRUM.



RADIATION CONVERSION CHART

FIGURE 1-3. NOMOGRAPH OF FREQUENTLY USED UNITS IN OPTICAL RADIATION

Light Scattering and Absorption

When light waves, which travel in straight lines, encounter any substance they are either scattered (transmitted and reflected) or absorbed. Scattered light refers to light waves that are not absorbed, but are transmitted or reflected from the surface of the media they encounter. On the other hand, if light strikes a medium and it is not scattered then it is absorbed. An explanation of the scattering of light is as follows. When light passes through the atmosphere, it is scattered by the large number of gas molecules and particles that make up the atmosphere. Objects are visible only because of the light they scatter toward the viewers' eyes. It is for this reason (i.e., the lack of light scattered toward them) that astronauts are largely in the dark when they travel in orbit beyond the earth's atmosphere. For this same reason, an observer may not see a light beam headed across his path. On the other hand, if smoke is blown into the path of a light beam, it immediately becomes visible.

This mechanism of optical scattering varies with the size of the scattering particles. Particles such as smoke may be considered large if their radii approach the wavelength of the incident light. The scattering from such particles is referred to as large particle scattering. In this type of scattering the particles may be considered as opaque spheres which scatter according to the principles of the diffraction theory. Particles whose radii are much smaller than the wavelength of the incident light (radius $<0.05\ \lambda$), scatter by a different mechanism called Rayleigh scattering. In this type of scattering, each microscopic particle acts as an electric dipole, re-radiating the incident wave by electrically coupling into resonance with the electric field of the incident light. This type of scattering can be seen by observing different regions of the daylight sky through a polarizing filter.

An explanation of the absorption of light is as follows. In passing through a material, light, like all electromagnetic radiation, undergoes absorption which can be expressed by the exponential relationship $I = I_o e^{-\mu x}$, where μ is a function of the absorbing material and the wavelength of the light, and x is the thickness of the absorbing material. If a green piece of cellophane is placed in the path of a red light beam, there is a substantial reduction in the beam intensity. If, on the other hand, a red piece of cellophane is used with the same beam, relatively little absorption occurs. This principle of selective absorption of light from light beams with given wavelengths is used to illustrate the effect of the wavelength on the absorption characteristics of the material used.

Summary of the Nature of Light

In order to fully understand the ability to see an object, we must understand what light is and how it reacts with matter. The previous sections attempted to give a general description of the nature of light that is summarized in the following:

- Light is a form of energy.
- Experiments show that light has the nature of particles and is propagated in waves.
- Visible objects give off light that enters our eyes.
- Luminous objects are a source of light.
- Nonluminous objects reflect light from another source.
- Light travels in straight lines as rays of light.
- Only the energy of a wave travels.
- The intensity of light is measured in candle power.
- Wavelength is the distance between two successive waves.
- Frequency is the number of waves passing a fixed point in one second.

- Visible light is a relatively small range of the electromagnetic spectrum.
- The speed of all electromagnetic waves is the same in a vacuum.
- The speed in more dense media is less, and varies with the wavelength.
- White light is made up of a mixture of wavelengths between about 0.4 and 0.7 microns.
- When an object reflects some of the wavelengths of light, but absorbs others, it gives a sensation of color.

We see things because of reflected light. Objects look different because they reflect light in a different manner. The difference in the intensity of light makes a difference in the visibility of an object. Color, likewise makes a difference in the visibility of objects. If one object absorbs twice as much color as another object, you have no difficulty in differentiating between them. You can therefore judge the size and shape of an object because of the difference in color or intensity of reflected light.

RADIOMETRIC AND PHOTOMETRIC QUANTITIES AND CONCEPTS *

The most confusing item for people when they first begin work in light is the perplexing system of units that are encountered. One reason for this is that the commonly used system of photometric units is defined in terms of the response of the human eye. Although some attempts have been made, photometric units have no real definition in the ultraviolet or infrared portions of the spectrum.

What makes the situation difficult is that most sensors are sensitive beyond the limits of the visible spectrum, and within the visible spectrum sensitivity often differs from that of the eye. Moreover, the response of the human eye is not constant. It varies among individuals and also with the level of illumination. Nevertheless, this section will attempt to cover and define the radiometric and photometric quantities and concepts related to this atmospheric visibility effort.

Elements of Radiometry and Photometry

Radiometry and photometry are the twin disciplines concerned with measuring the attributes of light within the context of carefully specified spectral and geometric constraints. The basic attribute is the rate at which electromagnetic energy, per stated spectral band, flows through a defined solid angle or area in particular directions. These geometric constraints may be associated with a material volume, a material surface, a conceptual surface, or free space itself.

The clearest meaning of an optical theory is achieved when it is expressed in radiometric or photometric terms. In turn, this allows the formulation of verifiable concepts. In a similar manner, the practical meaning of any optical phenomenon is found in its radiometric or photometric measurement. Thus any understanding of visibility through the atmosphere cannot be achieved without first acquiring some knowledge of the fundamentals of radiometry and photometry. Frequently, the mathematics of radiometry and photometry are complex, although the concepts remain simple. In what follows, an effort has been made to keep the mathematics to a minimum. Since they are basic to determining the quantitative characteristics of light, energy and energy flux will be defined as follows:

- <u>Energy</u>. The basic unit of radiant energy is the erg or joule (Joule = 10^7 ergs). The expression for energy was given in equation 1-3 and is repeated here,

$$P = hf = hc/\lambda, \qquad (1\text{-}3)$$

where,

$h = 6.624 \times 10^{-27}$ erg-second, and
$c = 3 \times 10^8$ meters/second.

*McCartney, E.J. (1976). Optics of the Atmosphere, John Wiley & Sons, N.Y.

Therefore, the energy associated with a light particle of 1 μ (10^{-6} meter) wavelength is about 2×10^{-12} ergs.

- Energy Flux. The amount of radiant energy that strikes a surface per unit time or is emitted per unit time is called radiant flux. The units are ergs/second, joules/second, or watts (1 joule/second = 1 watt). Thus, 1 watt of 1 μ light corresponds to about 5×10^{18} photons/second. When the radiant energy is at visible wavelengths, the flux can be called luminous flux and it is usually measured in lumens. The ratio of luminous flux to radiant flux is a measure of the ability to produce a brightness response. It is called luminous efficiency and is given in lumens/watt.

Response of the Eye

Photometry is the division of radiometry in which radiant flux is evaluated, not in absolute terms such as joules or watts, but in terms of its ability to evoke a visual sensation. As a result, photometry is the science which deals with the measurement of the quantitative characteristics of light. Flux so evaluated is called luminous flux, but the geometry parameters of distance, area, and angle are the same in photometry as in radiometry. To each radiometric quantity there corresponds a photometric quantity whose name is qualified by the adjective luminous. Because the eye was the original sensor, visual considerations were paramount in the early development of optics. Photometry thus preceded the larger field of radiometry. Of course, in the ultraviolet and infrared regions, photoelectric and thermal sensors are essential. Although instrumentation employing such sensors, as well as photographic film, has largely replaced the eye in photometric work, the objective of the measurements usually is to obtain results that agree with visual results. The eye therefore remains the ultimate judge of light in the narrow spectral region from about 0.38 to 0.76 microns and its responses to various types and levels of stimuli are the reference standards.

The human eye and its associated neural system constitute the most remarkable optical sensor of all time. The focusing properties and millions of separate retinal receptors arrange the incoming stimuli into a replica of the original spatial scene, whether the scene is 10 inches or 10 yards away. The ability to image a wide field with virtually no distortion is probably unmatched by any other optical sensor. The capabilities of adaptation enable the eye to function at starlight levels of illuminance as well as at sunlight levels which is an astounding dynamic range greater than one to one million. The relatively long time constant of the eye of approximately 0.1 seconds produces a persistence of vision without which all motion viewed by fluorescent lighting would exhibit intolerable stroboscopic effects.

The response of the eye to radiant flux at different wavelengths is shown in Figure 1-4. The curves reveal the relative efficiency of monochromatic flux, having constant power at each wavelength, in producing the sensation

of luminance (brightness) in the eye of a standard observer. Curve a refers to photopic vision which exists when a field luminance is approximately the luminance of a clear moonlit sky near the horizon. Curve b applies when the luminance is less than this condition. At such low levels the eye becomes dark adapted and the vision is scotopic. The eye is far more sensitive in scotopic than in photopic vision. Each curve has been normalized to unity at its maximum, so that it shows the relative luminous efficiency of radiant flux. The shift of the maximum to shorter wavelengths, as the field luminance is decreased, produces changes in the relative luminance of different colors.

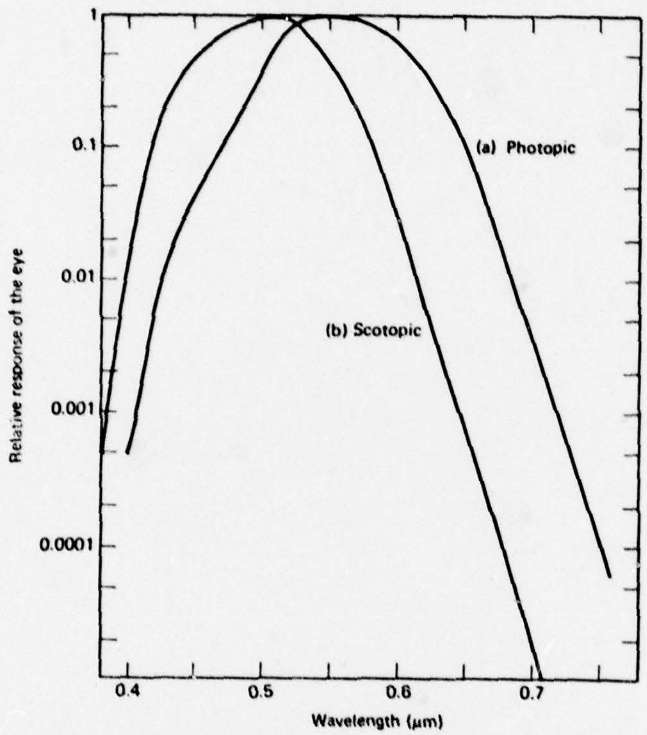


FIGURE 1-4.* RELATIVE SPECTRAL RESPONSE OF THE EYE AT PHOTOPIC AND SCOTOPIC LEVELS OF LUMINANCE.

For photopic vision, the peak response is at 0.55 microns. At this wavelength, 1 watt of radiant flux equals 680 lumens of luminous flux or 1 lumen equals 0.00147 watts. This is sometimes erroneously listed as the conversion factor for lumens and watts. However, the true conversion factor is a function of wavelength. If the distribution of wavelengths is known, it is possible to calculate an average luminous efficiency by integrating over the wavelength interval. For instance, it is found that the average efficiency

*Ibid, page 1-10

of a conventional light source rarely exceeds 50 lumens/watt. Table 1-1 lists the efficiencies of several light sources, beginning with the candle with an efficiency of 0.1 lumen/watt. The average luminous efficiency of sunlight is about 93 lumens/watt. A laser radiating at 5.55 microns is at the other extreme in efficiency of 680 lumens/watt.

TABLE 1-1. TYPICAL LUMINOUS EFFICIENCIES OF LIGHT SOURCES

LIGHT SOURCE	LUMINOUS EFFICIENCY (lm/W)	NOTES
Candle	0.1	
Kerosene Lamp	0.3	
120-V Tungsten	11.7	40-W, 2740°K
	16.3	100-W, 2845°K
	19.8	500-W, 2940°K
Mercury Arc	28	250-W, 68V
	65	1000-W, 840V
Fluorescent	61	54-W, 142V
Sunlight	93	
Laser	680	5.55 microns

Notes: w = watt, v = volt, lm = lumen

The concept of luminous efficiency, which is the same as visibility for the human eye, can be extended to any type of sensor. In general the efficiency curves are called spectral sensitivity curves or radiant energy response curves. Figure 1-5 shows the spectral sensitivity curve of the 7198 image orthicon along with the efficiency curve of the eye. It can be seen that the peak response falls almost outside the limits of human vision.

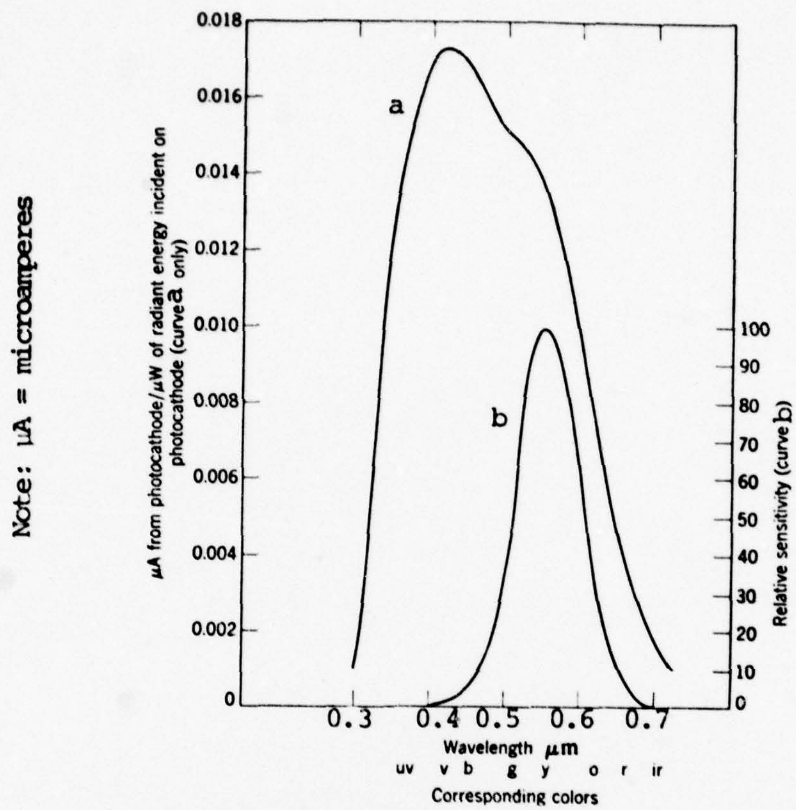


FIGURE 1-5.* SPECTRAL RESPONSE OF THE HUMAN EYE (CURVE a) AND A 7198 IMAGE ORTHICON (CURVE b)

Geometric Considerations

The propagation path of an electromagnetic wave in free space, ignoring any bending due to a gravitational field, is a straight line. Wave fronts, or surfaces of uniform phase, remain parallel to each other and perpendicular to the direction of travel. Indeed, such a path between a light source and a receiver provides the only operational or direct method of establishing a straight line. Straight-line propagation also holds for a material medium, provided that no gradient of refractive index exists normal to the path. Any such gradient causes a bending of the path toward the direction of the gradient. In the atmosphere, vertical gradients practically always exist, while horizontal gradients usually occur only infrequently and weakly.

Geometrically speaking, sources are classified as either point or extended sources. The first type radiates a spherical wave, while each elemental area of the second type radiates a spherical wave. The criterion for distinguishing between the two types is the ratio of the greatest projected dimension of the source to the path distance of interest, that is the plane angle subtended by the source. Astronomical objects are familiar examples. Stars, subtending angles less than 1 arc-sec, are point sources while the sun and moon, subtending angles of about 31 arc-min, are extended sources.

*Ibid, page 1-10

In practice, however, it is often convenient to observe the following rule. When the path distance is at least 20 times greater than the source projected dimension, the source can be regarded as a point source, with an error of 1% or less. In this case, the irradiance, which is the quantity of radiant flux incident per unit area of a surface normal to the path at any distance from the source, can be computed directly from the inverse-square law described below. When the prescribed dimension/distance criterion is not met, or when greater accuracy is wanted, the irradiance must be found by integrating over the solid angle subtended by the source.

Extended sources usually do not emit radiant flux uniformly with direction. Instead, most types of surfaces exhibit, to a varying extent, the cosine characteristic illustrated in Figure 1-6. Here the radiant flux element $d\Phi$ emitted within the elemental solid angle $d\omega$ varies with the angle θ from the surface normal according to

$$d\Phi_\theta = d\Phi_n \cos\theta \qquad (1\text{-}4)$$

This is Lambert's cosine law and surfaces whose elements obey this law, either for emission or for reflection, are called Lambertian or perfectly diffuse surfaces. A Lambertian surface is approximated by an optically rough or matted surface such as that of a blotter. Important also is the dependence of the effective emitting or reflecting area on the angle θ, the direction of interest makes with the surface normal, as shown in Figure 1-6. In all such cases, the effective area is the source area projected onto a plane normal to this direction.

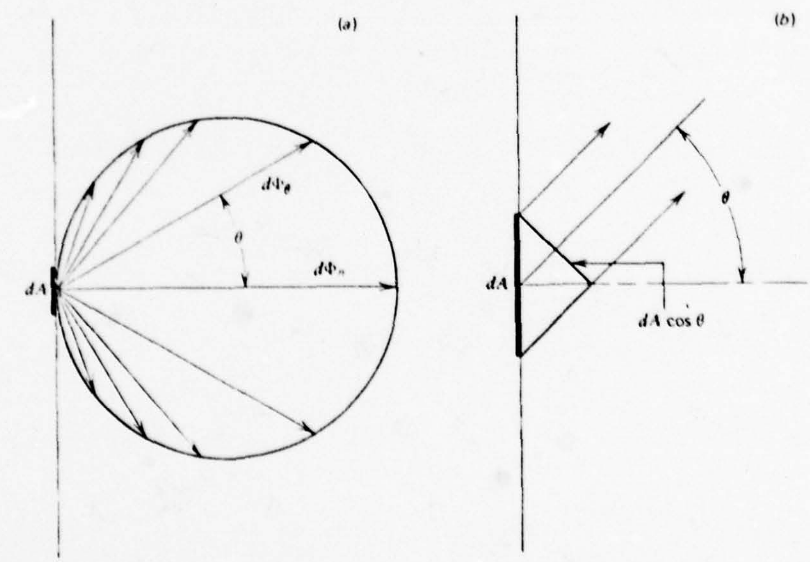


FIGURE 1-6.* VARIATION IN (a) FLUX REFLECTED OR EMITTED BY A DIFFUSE SURFACE AND (b) SOURCE PROJECTED AREA, WITH ANGLE FROM THE NORMAL.

*Ibid, page 1-10

As a consequence of the spherical wave emitted by a point source, the area of the expanding wave front increases as the square of the distance traveled. The irradiance of the surface then must vary inversely as the square of the distance from the source. The surface in question may be either a real one or a conceptual one representing the cross section of a light beam. In the general case the irradiance E at distance x is given by

$$E = \frac{I}{x^2} \cos \theta \qquad (1\text{-}5)$$

where I is the source intensity, or radiant flux per unit solid angle, and θ is the angle between the surface normal and the direction to the source. Equation (1-5) expresses the two basic laws of radiometry: the inverse-square law and the cosine law. Any beam of light, no matter how small its divergence angle, is subject to the inverse-square law.

Figure 1-7 is a graphic illustration of the inverse square law of light. It shows how the intensity of illumination may be measured. If a card is moved

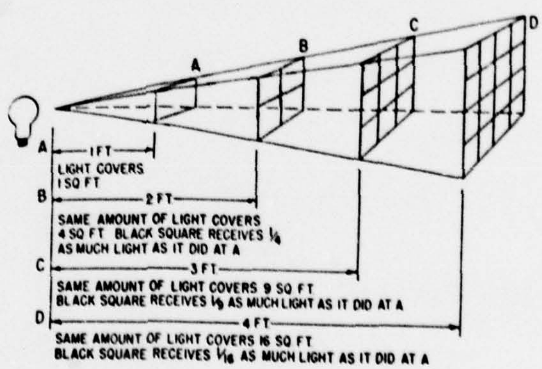


FIGURE 1-7.*,** INVERSE SQUARE LAW OF LIGHT.

two feet away, the intensity of the light decreases with the square of the distance (2 x 2, or 4 times) and is 1/4 as bright. If the card is moved three feet away, the decrease is 3 x 3, or the light is 1/9 as intense. If the card is moved four feet away, the light is 1/16 as intense.

* Opticalman, 1&C, Rate Training Manual, NAVTRA #10206-A, 1972

** Photographics Mate 2&3, Rate Training Manual, NavPers #10355-A, 1971

The inverse square law of light holds true for undirected light only; that is, light emissions not controlled by a reflector or condenser. For light that is directed, the rate at which its intensity diminishes is dependent upon the rate of divergence of the beam. In the case of a parallel beam, such as that from a searchlight, intensity is the same at all distances, except for that part of the beam lost to absorption by the intervening air. When the source is very distant or when beam-forming elements are used with a local source, the bounding rays of a selected beam may exhibit a very small divergence angle. The spatial scale of a particular experiment may then permit the divergence to be ignored, and the beam is said to be collimated. A beam of starlight is a nearly perfect example of collimated light from a distant source.

Radiometric Quantities*, **

The radiometric quantities are listed in Table 1-2, along with their definitions, symbols, dimensions and units. The basic symbols are the same as

TABLE 1-2. STANDARD SYMBOLS, DIMENSIONS AND UNITS OF THE RADIOMETRIC QUANTITIES.

Symbol	Quantity	Dimension	Common unit
Q_e	Radiant energy	ML^2T^{-2}	Joule (J)
W_e	Radiant density	$ML^{-1}T^{-2}$	Joule per cubic meter ($J\ m^{-3}$)
Φ_e	Radiant flux	ML^2T^{-3}	Watt (W) or joule per second ($J\ sec^{-1}$)
	Radiant flux density at a surface		
M_e	Radiant exitance (radiant emittance)	MT^{-3}	Watt per square centimeter ($W\ cm^{-2}$)
E_e	Irradiance	MT^{-3}	Watt per square meter ($W\ m^{-2}$)
I_e	Radiant intensity	ML^2T^{-3}	Watt per steradian ($W\ sr^{-1}$)
L_e	Radiance	MT^{-3}	Watt per square centimeter per steradian ($W\ cm^{-2}\ sr^{-1}$) Watt per square meter per steradian ($W\ m^{-2}\ sr^{-1}$)

Note: T = time in seconds.

the corresponding photometric quantities discussed in the section on photometric quantities and listed in Table 1-3 of that section. When it is necessary to distinguish between radiant and luminous quantities, the subscript e or v is added. For example, Q_e denotes radiant energy in Table 1-2 while Q_v would denote luminous energy.

* Ibid, page 1-10

** Bell, E.E. (1959). Radiometric Quantities, Symbols and Units, Proc. IRE, 47

Photometric Quantities*,**

The photometric quantities are listed in Table 1-3 where each one corresponds to a particular radiometric quantity of Table 1-2. In photometry, the unit of luminous flux (power) is the lumen, just as the watt is the

TABLE 1-3. STANDARD SYMBOLS, DIMENSIONS, AND UNITS OF THE PHOTOMETRIC QUANTITIES.

Symbol	Quantity	Dimension	Common unit
K	Luminous efficacy	—	Lumen per watt ($lm\ W^{-1}$)
V	Luminous efficiency	—	Numeric (0 to 1)
Q_v	Luminous energy (quantity of light)	ML^2T^{-2}	Lumen-hour (lm-hr) Lumen-second (lm-sec), talbot (T)
W_v	Luminous density	$ML^{-1}T^{-2}$	Lumen-second per cubic meter ($lm\text{-}sec\ m^{-3}$)
Φ_v	Luminous flux	ML^2T^{-3}	Lumen (lm)
	Luminous flux density at a surface		
M_v	Luminous exitance (luminous emittance)	MT^{-3}	Lumen per square foot ($lm\ ft^{-2}$)
E_v	Illuminance (illumination)	MT^{-3}	Footcandle ($lm\ ft^{-2}$) Phot (lm/cm^{-2}) Lux ($lm\ m^{-2}$)
I_v	Luminous intensity (candlepower)	ML^2T^{-3}	Candela ($lm\ sr^{-1}$)
L_v	Luminance (photometric brightness)	MT^{-3}	Candela per unit area Stilb ($cd\ cm^{-2}$) Nit ($cd\ m^{-2}$) Lambert ($cd\ \pi\ cm^{-2}$) Footlambert ($cd\ \pi\ ft^{-2}$) Apostilb ($cd\ \pi\ m^{-2}$)

Note: T = time in seconds

unit of radiant flux (power). The lumen is defined, however, not in terms of power as such, but in terms of a standard source. Originally this source was a standard candle, whose very name suggests that photometry is a traditional art. The brightness of this standard candle is approximately equal to the intensity of light from a 7/8-inch sperm candle burning at a rate of 120 grains per hour. Later, an international candle became the reference source, and this was variously reproduced in the form of calibrated gas flames and carbon filament lamps. The lumen is now defined as the luminous flux emitted into 1 steradian by a source whose luminous intensity is 1 candela. The candela is defined as one-sixtieth of the luminous intensity of a blackbody radiator, having an area of 1 cm^2, at the temperature of solidifying platinum (2042K). So defined, the candela is nearly equivalent

* Ibid, Page 1-10

** Rockwell, R. James, Jr. (Editor) et al (1977). Optical Radiation Measurements, 1st Edition, Published by CDI Seminar Mgt., Cincinnati, Ohio

to the old international candle standard. In order to simplify the conversion for these quantities, Tables 1-4 and 1-5 are included to indicate the conversion factors for illuminance and luminance.

TABLE 1-4. ILLUMINANCE (ILLUMINATION) CONVERSION FACTORS

1 lm = 1/680 lightwatt
1 lm-hr = 60 lm-min
1 ftcandle = 1 lm ft^{-2}
1 W-sec = 1 J = 10^7 ergs
1 phot = 1 lm cm^{-2}
1 lux = 1 lm m^{-2}

Number of → Multiplied by ↘ Equals number of ↓	Footcandles	Lux*	Phots	Milliphots
Footcandles	1	0.0929	929	0.929
Lux*	10.76	1	10,000	10
Phots	0.00108	0.0001	1	0.001
Milliphots	1.076	0.1	1,000	1

*The International Standard (SI) unit.

TABLE 1.5. LUMINANCE (PHOTOMETRIC BRIGHTNESS) CONVERSION FACTORS.

1 nit = 1 cd m^{-2}
1 sb = 1 cd cm^{-2}
1 apostilb (international) = 0.1 mL = 1 blondel
1 apostilb (German Hefner) = 0.09 mL
1 L = 1000 mL

Number of → Multiplied by ↘ Equals number of ↓	Foot-lamberts	Candela* per square meter	Milli-lamberts	Candelas per square inch	Candelas per square foot	Stilbs
Footlamberts	1	0.2919	0.929	452	3.142	2,919
Candelas per square meter (nit)*	3.426	1	3.183	1,550	10.76	10,000
Millilamberts	1.076	0.3142	1	487	3.382	3,142
Candelas per square inch	0.00221	0.000645	0.00205	1	0.00694	6.45
Candelas per square foot	0.3183	0.0929	0.2957	144	1	929
Stilbs	0.00034	0.0001	0.00032	0.155	0.00108	1

*International System (SI) unit.

REFLECTANCE AND CONTRAST

This section will briefly discuss reflectance and contrast since these are the primary parameters which affect the ability of the eye or a viewing instrument to detect an object. Contrast will be discussed in more detail in subsequent sections on the visual detection of objects.

Reflectance*,**

To the eye, the brightness or luminance of an object depends not only on the level of illumination, but also on how the object reflects the illumination. In general, the reflectance of a surface depends on the type of surface, on wavelength, which gives it color, and on the illuminating and viewing angles. The simplest type of reflection is specular or mirror reflection. When light strikes a mirror the angle of incidence and the angle of reflection are equal. If only a portion of the incident radiation is reflected, the surface has a reflectance, p, where p is the ratio of reflected to incident light.

$$p = \frac{\text{reflected radiation}}{\text{incident radiation}} \qquad (1\text{-}6)$$

Figure 1-8 illustrates the principle of light reflection back on its normal or perpendicular. When you hold the mirror perpendicular to a beam of light, you can reflect the beam back along the same path by which it entered.

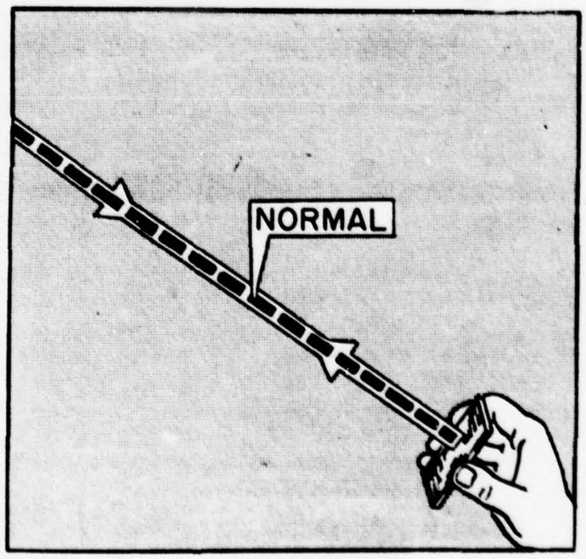


FIGURE 1-8.*,** RELFECTION OF LIGHT BACK ON ITS NORMAL OR PERPENDICULAR.

*,**Ibid, page 1-16

If you shift the mirror to an angle from its perpendicular position, the reflected beam is shifted at an angle from the incoming beam twice as great as the angle by which you shifted the mirror. As illustrated in Figure 1-9, if you hold the mirror at a 25^{o} angle with the incoming beam, the reflected beam is projected at an angle of 50^{o} to the incoming beam.

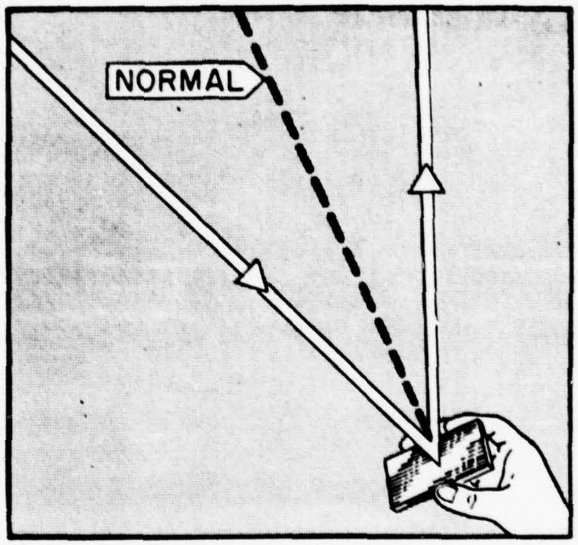
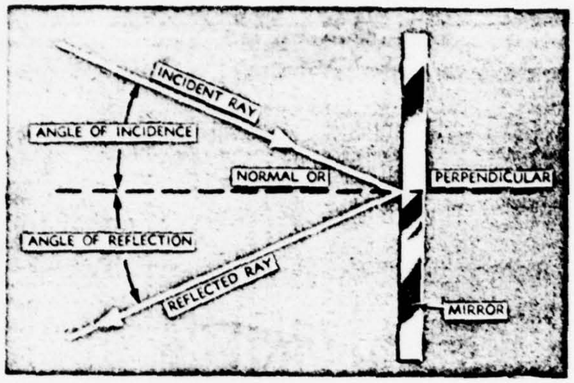


FIGURE 1-9.*,** REFLECTION OF LIGHT AT DIFFERENT ANGLES.

The simple reflectance characteristics of light just discussed illustrate one of the dependable actions of light. You can reflect light precisely to the point where you want it, because any kind of light reflected from a smooth, polished surface acts in the same manner. This effect is further illustrated in Figure 1-10. The ray of light which strikes the mirror is called the incident ray, and the ray which bounces off the mirror is known as the reflected ray. The imaginary line perpendicular to the mirror at the point where the ray strikes is called the normal or perpendicular. The angle between the incident ray and the normal is the angle of incidence, while the angle between the reflected ray and the normal is the angle of reflection.

*,**Ibid, page 1-16



*,** FIGURE 1-10. TERMS USED TO EXPLAIN REFLECTED LIGHT.

This leads directly to the law of reflection which is covered by the following three basic statements:

- The angle of reflection equals the angle of incidence.
- The incident ray and the reflected ray lie on opposite sides of the normal.
- The incident ray, the reflected ray, and the normal, all lie in the same plane.

As a result, whenever there is a mirror-like reflection in which the angle of reflection is equal to the angle of incidence, you have specular or commonly called regular reflection. Specular reflection can only come from a plane polished surface, and, if the incident light is parallel, the reflected light will be parallel as shown in Figure 1-11. Also, if the incident light is diverging or converging then the reflected light will be traveling in a like manner.

*,**Ibid, page 1-16

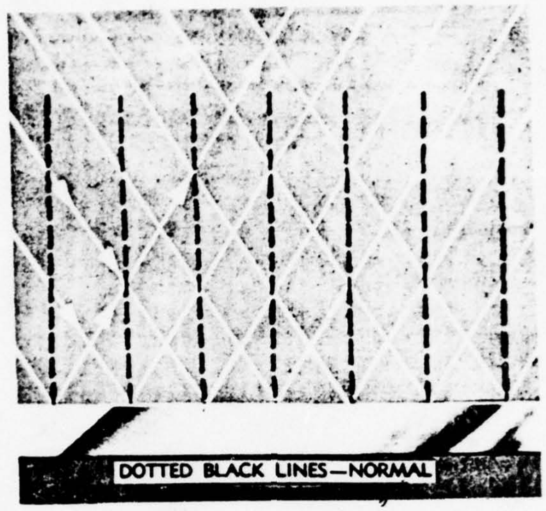


FIGURE 1-11.*,** REGULAR OR SPECULAR REFLECTION.

Most surfaces do not reflect light specularly but more or less diffusely. The antithesis of specular reflection is diffuse reflection and it will occur when light is reflected from a rough surface, or an object that has an irregular surface. Diffuse reflection is defined as a random distribution of included angles for a series of rays traveling from the same source. As shown in Figure 1-12, diffuse reflection is a scattering of the incident light and it accounts for ability to see all nonluminous objects as well as distinguish shape and texture.

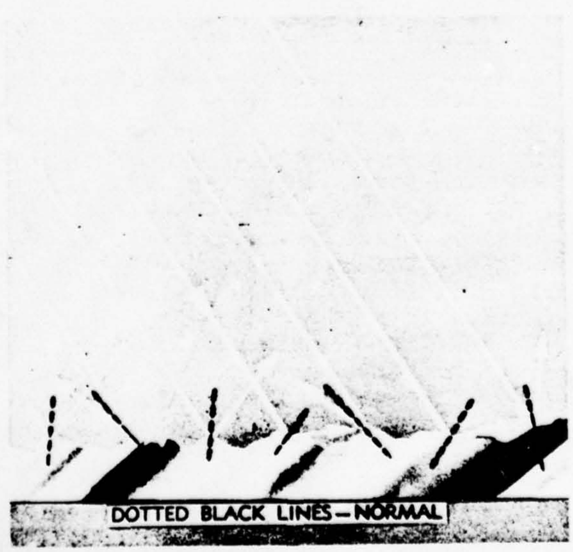


FIGURE 1-12.*,** DIFFUSE REFLECTION.

*,**Ibid, page 1-16

An object's reflectance depends on the time of day, time of year, latitude, viewing geometry, type of surface, atmospheric conditions, and wavelength of the irradiating light. The reflectance of any material changes primarily because of selective absorption at energies (or wavelengths) that correspond to the energy levels within the material. The energies are located throughout the electromagnetic spectrum depending on the type of transition or bond causing the absorption. If absorption causes an electron to move to a higher energy level, then the absorption spectra lie in the ultraviolet or visible wavelength regions. When the absorbed energies alter the vibrational energies between atoms, rather than electrons, the energy changes are lower, and the corresponding wavelengths fall in the near and middle infrared regions. Absorbed energies that alter the rotational energy levels between the atoms in a molecule are smaller still and the absorbed wavelengths fall in the far infrared and microwave regions. Table 1-6 lists the approximate reflectance (albedo) of various natural objects for visible wavelengths.

TABLE 1-6.* APPROXIMATE VISUAL REFLECTANCES OF VARIOUS EARTH SURFACES.

Surface	Approximate Albedo
Snow	0.70-0.86
Clouds	0.50-0.75
Limestone	0.63
Dry Sand	0.24-
Wet Sand	0.18
Bare Ground	0.03-0.20
Water	0.03-0.10
Forest	0.03-0.15
Grass	0.10-0.25
Rock	0.12-0.30
Concrete	0.15-0.35
Blacktop Roads	0.08-0.09

*Jensen, N. (1968), Optical and Photographic Reconnaissance Systems, John Wiley & Sons, Inc., New York

Contrast

This discussion on contrast will be brief because subsequent sections will cover contrast in more detail since it is a key parameter in the visual detection of objects.

An object is distinguished from its surroundings because of differences in brightness (luminance) and chromaticity between various parts of the viewed field. Such differences are usefully expressed as contrasts. Brightness contrasts are more important than chromaticity factors in determining visibility. Assume that an isolated object is viewed against a uniform, extended background. The object-background intrinsic contrast C_o is defined by

$$C_o = \frac{B_o - B_b}{B_b} = \frac{L_o - L_b}{L_b} \tag{1-7}$$

where,

C_o = intrinsic contrast of the object,

$B_o = L_o$ = intrinsic brightness of the object,

$B_b = L_b$ = intrinsic brightness of the background.

If $L_o < L_b$, the contrast is negative and becomes < 1 for an ideal black object if the background has any brightness at all. If $L_o > L_b$, as in the case of a light source seen against the night sky, the contrast may have a large positive value.

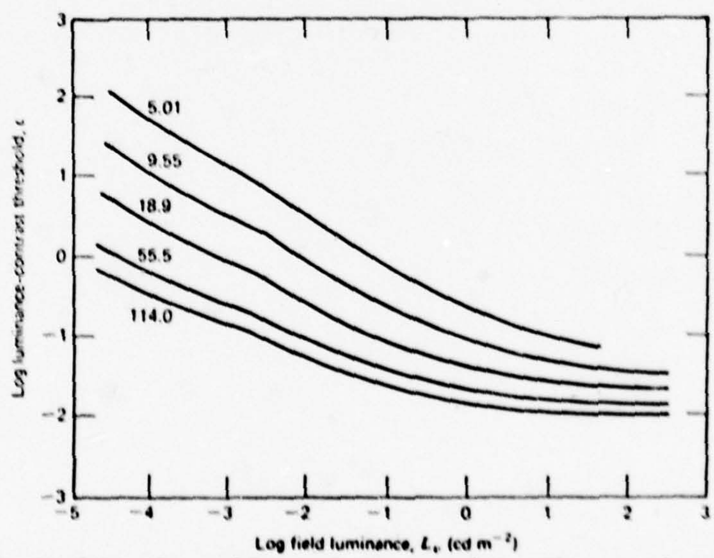
The eye has a very nonlinear response to changes in stimulus. This characteristic is undoubtedly associated with its ability to function well at brightness values differing by factors as large as 10^6. A general law of sensation, formulated by Weber (German physicist 1804-1891) in 1834 and known by his name, states: "The increase of stimulus necessary to produce a just perceptible increment of sensation bears a constant ratio to the whole stimulus." Application of this law to vision was investigated in 1859 by Fechner, (German physicist 1801-1887) who found that, when the field luminance changed from L_1 to L_2, the change in sensation was proportional to log $(L_2 - L_1)$. In other words, as the stimulus increased in geometric progression, the sensation increased in arithmetic progression. The "just perceptible increment of sensation" in the statement of Weber's law is the visual threshold of perception. Actually we are interested in two kinds of thresholds associated with two types of light sources in surrounding luminous fields. These types are (1) a luminous area and (2) a point source of illuminance. The two kinds of thresholds are discussed in the following paragraphs.

The first kind is a luminance-contrast threshold. In the present context this refers to the perception of a small target area within a large surrounding field. Let the luminances of target and field be made nearly equal, until the observer can just perceive a difference between the two. Denoting the luminances by L and L + ΔL, the threshold ε is defined as,

$$\varepsilon = \frac{(L + \Delta L) - L}{L} = \frac{\Delta L}{L}, \qquad (1\text{-}8)$$

where ΔL/L is the ratio of the least perceptible increment of field luminance to the field luminance itself. This ratio is called Fechner's fraction. Since the time of Fechner many investigations of this threshold have been made. In general they have shown that ε remains fairly constant for all values of L greater than about 1 cd m^{-2}, and for targets having angular subtenses greater than 1 degree. The value of ε is also affected by the presence of other stimuli in the field, by the psychophysical condition of the observer, and by the desired probability or assurance that the target has indeed been perceived, or detected.

Blackwell* (1946) presents extensive test data (the Tiffany Foundation data) on luminance-contrast thresholds. The tests employed targets that were brighter or darker than the surrounding field which formed a luminous background. The data represents thousands of observations made by many persons under controlled conditions. The angular diameters of the targets ranged from 0.6 to 360 arc-min, the field luminances varied from less than 10^{-5} to about 400 cd m^{-2}, and the resulting thresholds extended from less than 0.01 to more than 100. A small portion of the Blackwell data most relevant to the subject of visual range is plotted in Figure 1-13. The original data, which correspond to a detection probability of 50%, have been multiplied by the factor 1.62 to bring the probability up to about 90%. At field luminance greater than about 1 cd m^{-2}, the thresholds for the two largest targets remain essentially constant. Noteworthy are



NOTE: Number alongside each curve gives the angular subtense of the object in arc-minutes.

FIGURE 1-13.* LUMINANCE-CONTRAST THRESHOLD

* Blackwell, H.R. (1946). Contrast Thresholds of the Human Eye. J. Opt. Soc. Am. 36

the rapid increases in threshold for lesser luminances and smaller targets. The discontinuities in the curves at luminances near 2×10^{-3} cd m^{-2} mark the transition from foveal vision (photopic or light-adapted) to parafoveal (scotopic or dark-adapted) vision. Several sky conditions can be correlated with the values of luminance along the abscissa scale from the examples given in Table 1-7.

****

TABLE 1-7. APPROXIMATE LUMINANCE OF THE SKY NEAR THE HORIZON FOR VARIOUS CONDITIONS

Condition	Candelas per square meter
Clear day	10^4
Overcast day	10^3
Heavily overcast day	10^2
Sunset, overcast day	10
One-quarter hour after sunset, clear	1
One-half hour after sunset, clear	10^{-1}
Fairly bright moonlight	10^{-2}
Moonless, clear night sky	10^{-3}
Moonless, overcast night sky	10^{-4}

Note: Extreme meteorological conditions may cause the luminance to vary by a factor of 10 or more.

The second kind of visual threshold important in atmospheric optics is the threshold for point sources of light. A point source is defined as a stimulus that affects the eye only in proportion to its intensity. The maximum diameter of a point source observed with the unaided eye can vary from 1 arc-min or even less, at field luminances greater than about 1 cd m^{-2}, to 10 arc-min for dark-adapted parafoveal vision. The threshold is basic to the visual detection of signal lights and beacons and to the visibility of stars. It is stated not in terms of luminance contrast as for extended sources, but in terms of the illuminance produced at the eye by the point source. Such thresholds have been investigated by Green* (1932) and Knoll et al. (1946)**. The Blackwell (1946)*** data for very small targets are also applicable when treated by the method of Middleton (1958),**** who discusses and compares the results of all three investigations. Data from these investigations are plotted in Figure 1-14. The Green and Knoll curves correspond to a practical certainty of detection, while the Blackwell curve corresponds to a 50% probability. If the Blackwell curve is raised by 0.3 log units to represent a practical certainty, the three curves agree well at the lower values of luminance.

* Green, H.N. (1932). The Atmospheric Transmission of Coloured Light. RAE Rept. E and 1. Royal Aircraft Establishment, Farnsborough, England.

** Knoll, H.A., et al (1946). Visual Thresholds of Steady Point Sourcs of Light in Fields of Brightness from Dark to Light. J. Opt. Soc. Am., 36

*** Blackwell, H.R. (1946). Contrast Thresholds of the Human Eye. J. Opt. Soc. Am. 36

****Middleton, W.E.K., (1958). Vision Through the Atmosphere. Univ. of Toronto Press

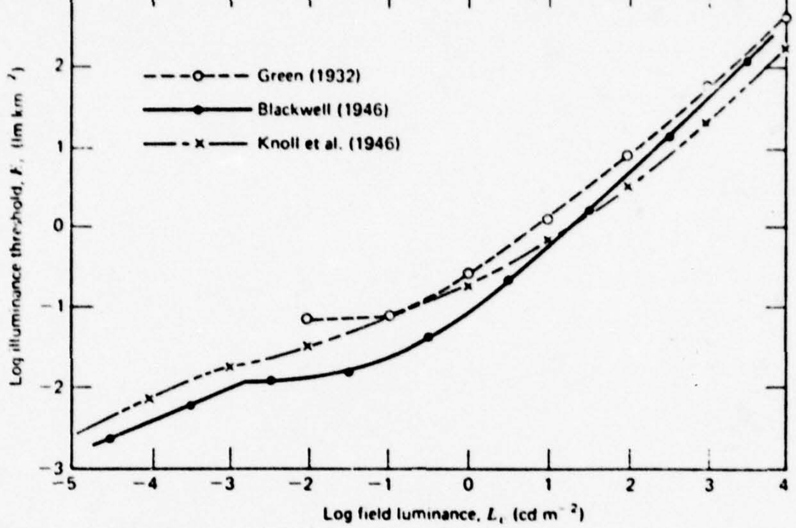


FIGURE 1-14.*,**,*** ILLUMINANCE THRESHOLD AS A FUNCTION OF FIELD LUMINANCE.

As was mentioned previously, the subject of contrast will be covered in more detail when addressing the visual detection of objects.

*,**,*** Ibid, page 1-27

ATMOSPHERIC ATTENUATION *,**

This section will deal, in a general manner, with atmospheric attenuation and its effects on visibility. Later sections will deal with these effects in more detail. The basic attenuation mechanisms are scattering and absorption and these will receive the greatest attention in this section. In addition, other atmospheric attenuation mechanisms, such as atmospheric turbulence which includes thermal stratification, will be briefly discussed.

The scattering of light from small particles or moisture droplets suspended in the atmosphere and the absorption of light has a two-fold effect on the propagation of light from an object to an observer. First, light coming from an object of interest and from its background is progressively removed from the viewing path and does not reach the observer and, second, light which has not come directly from the object or from its immediate background is scattered into the viewing path. These effects will be examined in this section.

Distinction Between Scattering and Absorption

Scattering must be distinguished from absorption. Both processes remove flux from a given beam of light, but the similarity ends there. Scattering is explained in terms of the wave theory of light, and it produces no net change in the internal energy states of the molecules. In contrast, absorption requires quantum theory for its explanation and does produce changes in the internal energy states.

- Scattering. Scattering is explained in terms of the electromagnetic wave theory and the electron theory of matter. Briefly stated here, the electric field of the incident or primary wave sets into oscillation the electric charges of the particle, whether it is a molecule or a cloud droplet. The oscillating charges constitute one or more electric dipoles which radiate secondary, spherical waves. Since the charges oscillate synchronously with the primary wave, the secondary waves have the same frequency and wavelength as the primary wave, and they bear fixed phase relations to it. Timewise, the scattering process is a continuous one and, when averaged over complete cycles, produces no net change in the internal states of the particle. Spectrally, the process is also continuous, although it is strongly dependent on wavelength for a particle of given size. Even if the incident light is unpolarized, the scattered light is polarized to some extent. The type and degree of polarization depend on the optical properties of the particle, the polarization of the incident light, and the direction in which the scattered light is observed. When the particle is isotropic, the scattered intensity referred to a particular polarization is a function of particle size, particle relative refractive index, and wavelength of the incident light. These are the three parameters of scattering. To the extent that they are known, the scattering pattern can be accurately predicted from theory. Speaking broadly, the scattering process has two observable aspects. When the scattered intensity is of concern, as in studies of skylight, we deal with angular scattering. When the total flux removed from a light beam is of concern, as in studying the attenuation of sunlight, we deal with total scattering.

* Ibid, page 1-10

**Zuev, V.E. (1974). Propagation of Visible and Infrared Waves in the Atmosphere. Halstead Press, N.Y.

- Absorption. Figure 1-15 depicts a simplified energy level diagram for a one electron atom that will be used to explain absorption. The relationship between the electrons and the nucleus of the atom is described in terms of discrete energy levels.

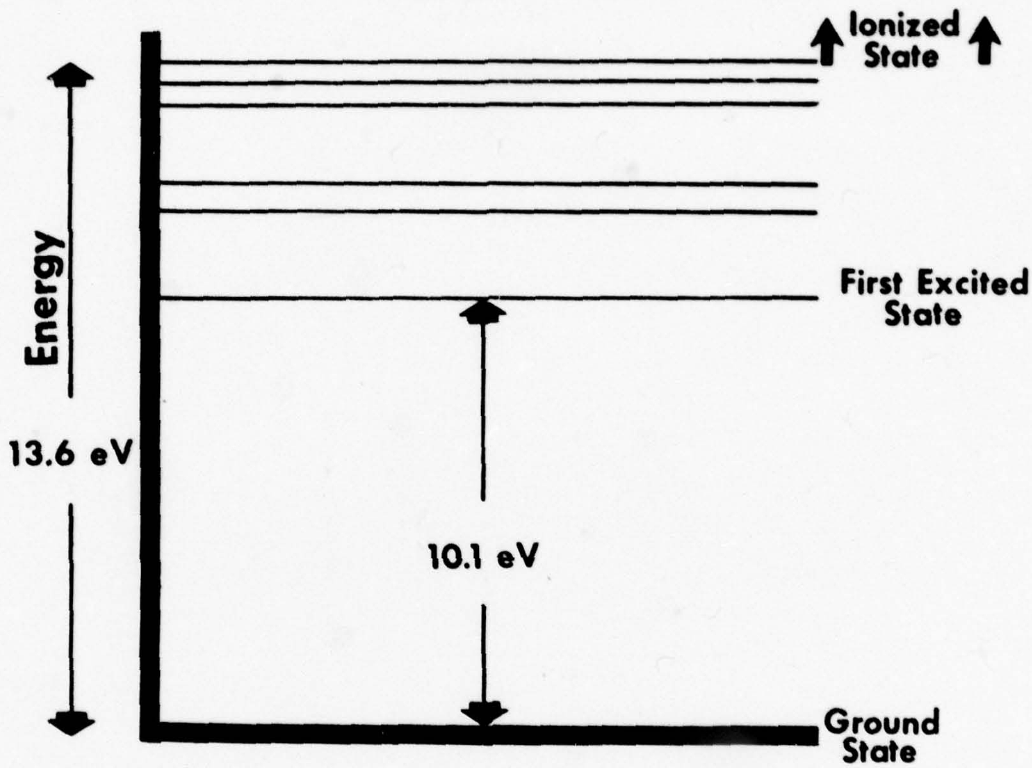


FIGURE 1-15. TYPICAL ENERGY LEVEL DIAGRAM

The electrons normally occupy the lowest available energy levels. When this is the case, the atom is said to be in its ground state. However, electrons can occupy higher energy levels, leaving some of the lower levels vacant. The electrons change from one energy level to another by the absorption or emission of energy. During absorption, a quantum of energy is absorbed by the atom thereby undergoing a transition from a lower to a higher energy state. This increase in the energy of the electron causes it to jump to a next higher energy level and the atom is then in the excited state. It is important to note that an electron accepts only the precise amount of energy that will move it from one allowable energy level to another. Therefore, only those photons of the energy or wavelength acceptable to the electron will be absorbed. Timewise, absorption is a discontinuous process because of the quantizations. Spectrally the process is selective, not continuous, because only those quanta can be absorbed whose energies are equal to the differences between the permitted levels.

Principal Characteristics of Scattering

In a previous section, the radiometric and photometric principles were covered, and with those in mind, we now look at the basic scattering process and consider the several types of scattering that occur when a light wave is incident on a particle. This is done first in terms of a single isolated particle where the effects of particle size relative to wavelength are described. The ideas are then extended to the case of a group of particles scattering in proximity to each other, thus creating composite effects.

Scattering is the process by which a particle, any bit of matter, in the path of an electromagnetic wave continuously (1) abstracts energy from the incident wave, and (2) reradiates that energy into the total solid angle centered at the particle. The particle is a point source of the scattered (reradiated) energy. For scattering to occur, it is necessary that the refractive index of the particle be different from that of the surrounding medium. The particle is then an optical discontinuity, or inhomogeneity, to the incident wave. When the atomic nature of matter is considered, it is clear that no material is truly homogeneous in a fine-grained sense. As a result, scattering occurs whenever an electromagnetic wave propagates in a material medium, such as the atmosphere. Table 1-8 shows the wide ranges of particle size and concentration that are responsible for scattering in the atmosphere.

TABLE 1-8.* PARTICLES RESPONSIBLE FOR ATMOSPHERIC SCATTERING

Particle Type	Radius (microns)	Concentration (cm^{-3})
Air molecule	10^{-4}	10^{19}
Aitken nucleus	10^{-3} - 10^{-2}	10^{4} - 10^{2}
Haze particle	10^{-2} - 1	10^{3} - 10
Fog droplets	1 - 10	100 - 10
Cloud droplet	1 - 10	300 - 10
Raindrop	10^{2} - 10^{4}	10^{-2} - 10^{-5}

The intensity of the scattered radiant energy, also called the scattered intensity, forms a characteristic three-dimensional pattern in space about each particle. If the particle is isotropic, the pattern is symmetric about the direction of the incident wave. The form of the pattern depends strongly on the ratio of particle size to the wavelength of the incident wave, as illustrated by the three examples in Figure 1-16. In Figure 1-16a, the relatively small particle tends to scatter equally into the forward and rear directions. In Figure 1-16b, when the particle is larger, the overall scattering is greater and more concentrated in the forward direction. In Figure 1-16c, for a still larger particle, the overall scattering is even

* Ibid, page 1-10

greater and most is concentrated in the forward direction with secondary scattering in various other directions. Further increases in particle size produce patterns of even greater complexity. In all cases the form of the pattern is influenced by the relative refractive index, that is, the ratio of the refractive index of the particle to that of the medium surrounding the particle.

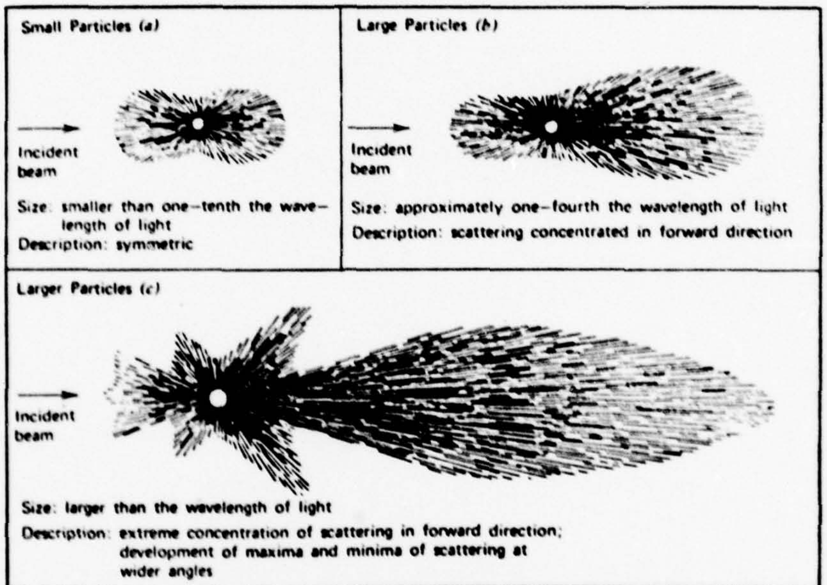


FIGURE 1-16.* ANGULAR PATTERNS OF SCATTERED INTENSITY FROM PARTICLES.

The wide range of particle size in Table 1-8, covering orders of magnitude, suggests that scattering itself may show large variations as can be seen in Figure 1-16. The three types of scattering that will be covered are Rayleigh, Mie, and nonselective scattering.

- Rayleigh Scattering. Rayleigh scattering occurs when the particle is far smaller than the wavelength of light. Scattering of this type varies directly as the second power of the particle volume and inversely as the fourth power of the wavelength. This means that blue light with a wavelength of 0.45 microns is scattered about six times as strongly as red light with a wavelength of 0.7 microns. This rapid increase in scattering as wavelengths become shorter explains the red color of the sun at sunrise and sunset as well as the blue color of the sky. Sunlight traveling through the air scatters blue light strongly in all directions. If we look at a beam of sunlight from the side, it appears blue. On the other hand, if we look through enough atmosphere toward the sun, it appears red because the shorter wavelengths have been scattered away. As a result, equal amounts of flux are scattered into the forward and back hemispheres, as in Figure 1-16a. The principal Rayleigh scatterers in the atmosphere are the molecules of atmospheric gases.

* Ibid, page 1-10.

- <u>Mie Scattering</u>. On very clear days, the measured scattering in the atmosphere closely matches the calculated Rayleigh scattering. However, as the particles increase in size and visibility decreases, Mie scattering begins to predominate, and the calculations become far more difficult to make and check. This occurs when the particles range from roughly 1/10 of a wavelength to 10 wavelengths in size. As a result, when the particles diameter is greater than about 1/10 of the wavelength, Rayleigh theory is not adequate to explain the phenomena and Mie theory is used. Although Mie theory is strictly applicable only to isotropic spheres, it is customary to employ the term Mie scattering even though the particles may be somewhat irregular in shape. The full Mie theory is expressed as a mathematical series embracing all particle sizes where the first term of the series is equivalent to the Rayleigh expression. For spheres of great relative size, such as raindrops illuminated by visual light, the Mie theory can be closely approximated by the principles of reflection, refraction, and diffraction. Every particle in the atmosphere is actually a Mie scatterer, but we apply the term only to particles larger than Rayleigh scatterers.

- <u>Nonselective Scattering</u>. Scattering becomes nonselective as the scattering particles become larger than about 10 wavelengths. When this occurs, all colors scatter equally well, which accounts for the white appearance of clouds. As a result, the larger particles scatter more light. Therefore, nonselective scattering results in greater scattering of light than Mie or Rayleigh scattering.

Since larger particles scatter more light, the scattering depends only on the actual cross section and density of the particles. The major factor is water vapor, although smoke and dust can also be important. The usual procedure is to estimate the amount of precipitable water in a path length and then consult tables to find the transmission for the path. Figure 1-17 shows how the scattering coefficient varies with wavelength for different sizes of particles. It should be noted that if the scattering particles are classed as smoke or haze, the scattering coefficient in the infrared is significantly improved over the visible. This fact is sometimes used to advantage when visibility is limited by smoke or haze, However, it can be seen that the ability to penetrate fog or rain is essentially no better in the near-infrared than the visible. The improvement begins at wavelengths of about 20 microns or greater, again depending on the size of the scattering particles. For heavy rain, in which the drops may have a diameter of about 100 microns, Rayleigh scattering will still be significant with millimeter-wavelength radar. Table 1-9 shows the approximate diameters of scattering particles for various atmospheric conditions.

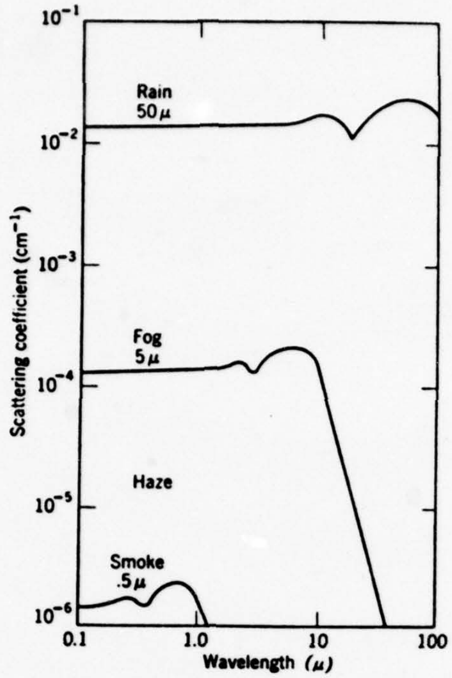


FIGURE 1-17.* THE SCATTERING COEFFICIENT AS A FUNCTION OF WAVELENGTH AND PARTICLE SIZE.

TABLE 1-9.* APPROXIMATE DIAMETERS OF PARTICLES SUSPENCED IN THE ATMOSPHERE.

Particle	Approximate Particle Diameter (microns)
Smoke	Smaller than 1: tobacco smoke, 0.2 or less; smoke from burning oil, up to about 1:general, 0.001-0.1
Fumes	0.1-1, but in case of industrial smelter fumes may range up to 100
Haze	Less than 1, generally 0.001-0.1
Dust	1 and bigger, but generally larger than 10, dust from rock drilling, majority below 2-5, but many over 10
Fog, Cloud	5-50
Mist	50-100
Drizzle	100-400
Rain	400-4,000

NOTE: These values are only approximate, as much depends on the nature of the particles, the mode of formation, and the state of disturbance of the atmosphere.

* Ibid, page 1-10

In the discussion to this point, single scattering has been assumed in that the particle is exposed only to the light of an incident or direct beam. No account has been taken of the fact that each particle in a scattering volume is exposed to and also scatters a small amount of the light already scattered by the other particles. This light, very weak by comparison with that of the direct beam, reaches a given particle from many directions, as shown by Figure 1-18. Therefore, some of the light that has been first-scattered may be rescattered one or more times before emerging from the scattering volume. This is called secondary or multiple scattering. Although multiple scattering has little effect on the total amount of light removed from the direct beam, it may significantly alter the composite pattern of scattered intensity due to all the particles.

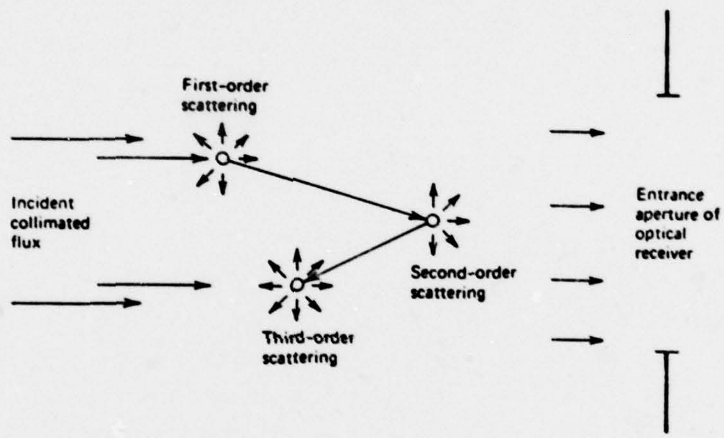


FIGURE 1-18.* MULTIPLE SCATTERING OR RESCATTERING OF ONCE-SCATTERED LIGHT.

This characteristic of multiple scattering can be appreciated from Figure 1-16. For example, visualize that the pattern in Figure 1-16c is overlaid with a multitude of similar but far weaker patterns having all orientations in the plane of the figure. It becomes clear that the composite pattern, while still retaining the principal features of the original, exhibits fewer and smaller variations in intensity as a function of angle. In the extreme, as with a very turbid medium, all sense of the direct beam is lost, and the scattered light tends to reach an observer rather uniformly from all directions. This tendency is manifested in a dense fog.

* Ibid, page 1-10

Principal Characteristics of Absorption

The absorption of radiation by a clean atmosphere is greatest in the infra-red and ultra-violet regions of the spectrum. The absorbing agents are mainly water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), ozone (O_3), molecular and atomic oxygen (O,O_2), and molecular and atomic nitrogen (N,N_2). In the infra-red there are discrete absorption bands, while in the ultra-violet the transmission at wavelengths below 0.3 microns is very low. In the visible region, there is little absorption on a clear day, and it is generally negligible when the water content is low. For the visible wavelengths, roughly 0.38 to 0.76 microns, nearly all the absorption is because of the water vapor in the atmosphere. In the infrared region the absorption results from the presence of water vapor, carbon dioxide, nitrous oxide, and ozone. In the ultraviolet everything absorbs at some wavelengths. From 0.22 to 0.13 microns, the absortion is due to ozone. It should be pointed out that ozone is not present in the lower atmosphere where this atmospheric visibility report is being addressed. Below 0.13 microns, the absorption is caused mainly by atomic and molecular nitrogen and oxygen.

The situation is rather different in regions where the atmosphere is polluted with industrial waste. A suspension of black soot particles is a strong absorber. In fact, with such atmospheres, absorption has been found to be very dependent on the particular conditions, both in magnitude and spectral properties. A great deal of practical field measurements of attenuation in such conditions as industrial haze suggests that it is difficult to predict the absorption properties in a given situation. Thus it has become fashionable to assume that, in most viewing situations, it can be ignored as a separable function. This is probably satisfactory in most instances. However, it can be dangerous to ignore absorption without due thought where light is being added to a viewing path as well as removed from it, (the usual daylight viewing situation), since in this case light added to the path is only added by scattering, while that removed may include a major contribution due to absorption.

Because of the strong absorption bands in the ultraviolet, there is very little transmission through the atmosphere at wavelengths below 0.3 microns. The infrared, however, displays several transmission bands as shown in Figure 1-19. Continuing past the infrared into the microwave region, transmission again becomes generally excellent. Figure 1-19 illustrates the basic absorption bands throughout these wavelength regions. The transmission path is from sea level vertically through the atmosphere on a clear day where only a minimal amount of water vapor is present.

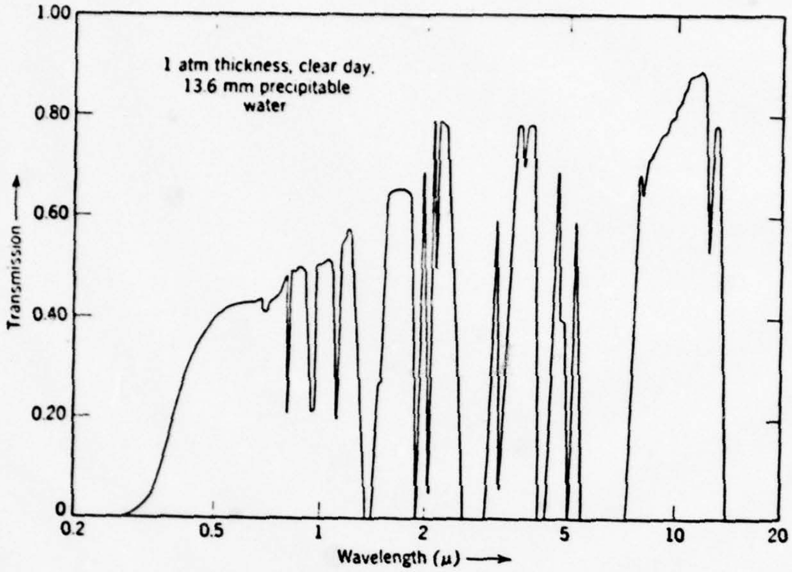


FIGURE 1-19.* TRANSMISSION FROM SEA LEVEL VERTICALLY THROUGH A CLEAR ATMOSPHERE.

Atmospheric Turbulence

In the previous sections, we assumed that light scattering, absorption, and attenuation operate independently of spatial frequencies. However, this assumption is true only for uniform, nonturbulent atmospheres. Real atmospheres exhibit turbulence. The optical effects of the turbulence result from the changes in the index of refraction of the air, which varies because of changes in pressure and temperature. As a result, thermal currents, thermal stratification, updrafts, and other atmospheric turbulence will cause the index of refraction to vary in a complicated way. In some instances the changes within a narrow column of air may appear as a lensing action that throws an image in and out of focus. The result is a twinkle in intensity known as scintillation. The lensing action may also magnify or demagnify the image resulting in a phenomenon known as pulsation. However, the major effects of atmospheric turbulence are caused by random bending or distortions of the wavefront. How seriously these distortions affect visibility of an object depends on a great many things, including the following:

- Obviously the image motion depends on the degree of turbulence. In general the turbulence is greater in daytime than at night, greater in winter than in summer, greater near oceans or irregular land features than over deserts or smooth terrain, and greater in regions of substantial temperature differences. In general, seeing conditions are usually classed simply as good, average, or poor. If it is possible to wait indefinitely for a picture (for instance an astronomer taking pictures of the moon), then sooner or later good or excellent seeing conditions will exist. Unfortunately, this rarely occurs.

*Taylor and Yates (May 1956), Atmospheric Transmission in the Infrared, Report on NRL Progress, pp 9-16.

- Image motion depends on the viewing angle. It is minimal when looking in a vertical direction, either up or down. Image motion as a function of elevation angle is plotted in Figure 1-20 for good, average, and poor seeing.

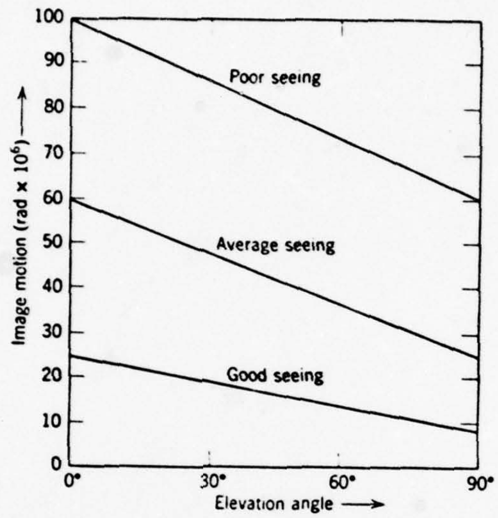


FIGURE 1-20.* IMAGE MOTION AS A FUNCTION OF ELEVATION ANGLE FOR GOOD, AVERAGE, AND POOR SEEING CONDITIONS.

- Small image motions are more probable than large ones. This means that there is a time frequency associated with the motions and a long exposure creates more blur than a short one.

- The magnitude of the image motion depends on how far the observer is from the turbulence. The closer the turbulence, the larger the motion. The decrease in motion with elevation angle (Figure 1-20) is really an aspect of this principle. Thus seeing will be different for an observer above the atmosphere looking at the ground than for an observer on the ground looking into space. If the sensor is far above the atmosphere, say in a satellite, nearly all the light rays deviated by the atmosphere will miss it, and the angular deviation of the image must therefore be small. On the other hand, if the sensor is on the ground, deviations may occur very near it so that some light rays will arrive with large angular deviations. When sensor and object are both within the atmosphere, the analysis is more complicated. The effect can be demonstrated with a sheet of translucent material or window screen. Close up, vision through it is noticeably worse than when the material is held at arm's length.

* Ibid, page 1-10

- The larger a lens, the more light rays it averages in any instant. Because the motions are random, increasing the aperture of a sensor will improve the average. However, it is statistically possible, at any instant, to have no random motions, so that if a lot of pictures are taken with a small, fish lens some of the pictures may be better than those taken with a large lens.

- Increasing focal length magnifies the linear motion from turbulence. Thus very large telescopes do not distinguish lunar details any better than relatively small telescopes. (Large telescopes are made large so as to collect more light from faint stars.)

<u>Forms of Degradation Due to Turbulence</u>

Variations in the angle of arrival of a received optical wave-front will cause an image to be focussed at different points in the focal plane of the receiving optics. This results in a continuous, rapid movement of the image about a mean point, and is known as image motion or image dancing. Particularly slow oscillatory motions of this form are called wanderings or beam steering and are due to deviations of the entire beam from the line of sight. The terms pulsation or breathing are used to describe a fairly rapid fluctuation of the cross-section of a propagated light beam due to small angle scattering by the atmospheric inhomogeneities. This scattering also produces destructive interference within the beam, which in turn produces local fluctuations in amplitude and therefore intensity (scintillation). These intensity fluctuations appear as areas of bright and dark compared to the average intensity over the beam cross-section. Scintillation refers only to rapid fluctuations in intensity, and, in particular, applies to point light sources (e.g., the twinkling of stars). Image distortion of blurring is the integrated effect of image motion and pulsation involving many points which form the details of an extended object. It is clear that if such points move independently of, and out of phase with, one another, the details become blurred, lose contrast and cannot be distinctly recovered from the image. This is often loosely referred to as boiling which means the time-varying non-uniform illumination of a large spot image. Shimmer is a general term often given to the tremulous appearance, apparent distortion, and motion of an object seen, for instance, through a layer of air immediately above a heated surface. All of these forms of degradation due to turbulence affect the seeing quality or the quality of image transmission through the atmosphere. This, in turn, affects the capability of the eye or a viewing instrument in the detection of an object.

2. VISUAL DETECTION *,**,***,****,*****

Before proceeding into the effects of atmospheric obstructions on visibility, it becomes necessary to discuss and develop an approach for determining the visual detection of objects, the maximum range at which a target can be seen, and the chance that the target will be seen while it is at any given range. For visual detection, this requires some knowledge of the construction and performance of the eye as a detecting instrument. Later, other detecting instruments will be addressed.

THE HUMAN EYE ****,*****

Of all the optical systems, the most important is the human eye and an understanding of its function will help to comprehend more clearly the use of the human eye and other optical instruments in detecting objects. A complete study of the human eye involves physiological and psychological aspects since any image formation must be interpreted by the human brain. The human eye is in effect a physical image-forming system that has lenses of certain curvature and measurable indices of refraction. The eye conforms to the usual laws of image formation when producing an image on a sensitive screen in the back of the eye known as the retina. To see and distinguish an object, light of suitable quality and intensity from the object must form an image on the retina which transforms the light energy to nerve energy. The nerve impulses are then conducted to the brain by the optic nerve and we are able to distinguish the object.

Eye Structure

As illustrated in Figures 2-1 and 2-2, the human eye is a nearly spherical organ held in shape by a tough, outer, whitish sclerotic coat, called the sclera, and the pressure of its viscous content. The cornea, the transparent front part of the sclera, protrudes slightly as it has a greater curvature. Inside the sclera is the choroid containing blood vessels, the opaque pigment (not shown), and the ciliary process. The ciliary process includes the iris and the muscles which focus the lens of the eye. The pupil is the opening in the center of the iris. The retina covers the inside of the choroid up near the ciliary muscle. The space between the cornea and the iris is called the anterior chamber and between the iris and the lens is the posterior chamber. Both are filled with a fluid called the aqueous humor.

* McCartney, E.J. (1976). Optics of the Atmosphere, John Wiley & Sons, N.Y.
** Jensen, N. (1968). Optical and Photographic Reconnaissance Systems. John Wiley & Sons, N.Y.
*** Koopman, B.O. (1946). Search and Screening, U.S. Navy, Chief of Naval Operations, Operations Evaluation Group, Report 56
**** Opticalman 1&C, Rate Training Manual, NAVTRA #10206-A, 1972
***** Photographic Mate 2&3, Rate Training Manual, NavPers #10355-A, 1971

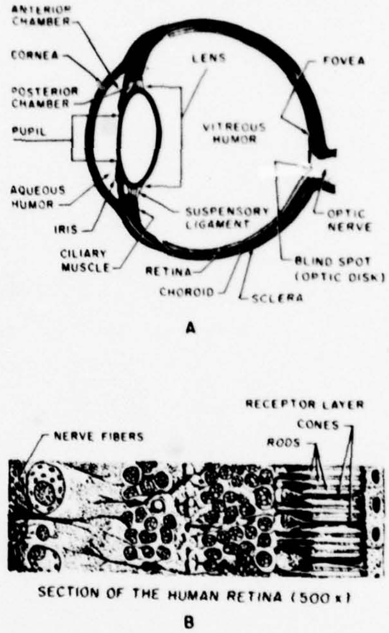


FIGURE 2-1.*,** CONSTRUCTION OF THE HUMAN EYE

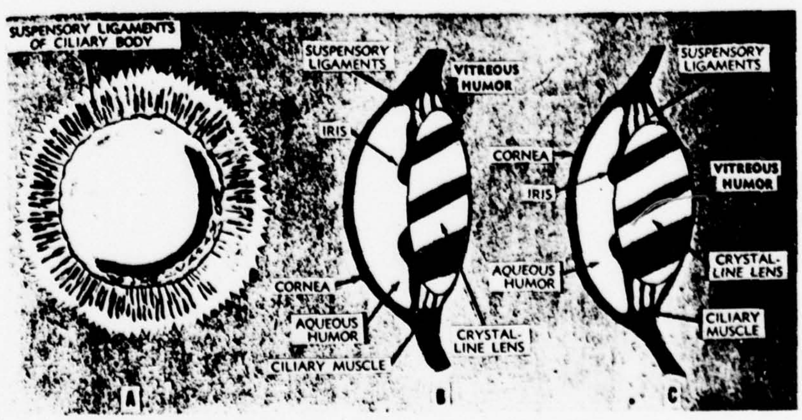


FIGURE 2-2.*,** SUSPENSION AND ACTION OF THE LENS

The space behind the lens and the ciliary process is filled with the vitreous humor. The lens is attached to the ciliary muscle by many fibers called suspensory ligaments, as shown in Figure 2-2A. Except for the opening in the iris, called the pupil, the pigmentation of the sclera and iris normally makes the eye light tight. Without proper pigmentation, vision is impaired by glare from light leakage onto the retina.

* Opticalman 1&C, Rate Training Manual, NAVTRA #10206-A, 1972
** Photographics Mate 2&3, Rate Training Manual, NavPers #10355-A, 1971

Comparison With a Camera

In general construction, the eye is very similar to a camera as shown in Figure 2-3. The camera is a physical optical instrument that forms an image on the sensitized film which, when processed, becomes a photograph. The formation of an image by the human eye is a physical optical instrument only to the point of refracting light. From the formation of an image on the retina of the eye, the balance of seeing is a psychological processing dealing with nerve impulses and the brain. The only comparisons of physical properties of the eye that can be made with the camera are lens with lens, iris with diaphram, and sclera with the lightpoof housing of the camera.

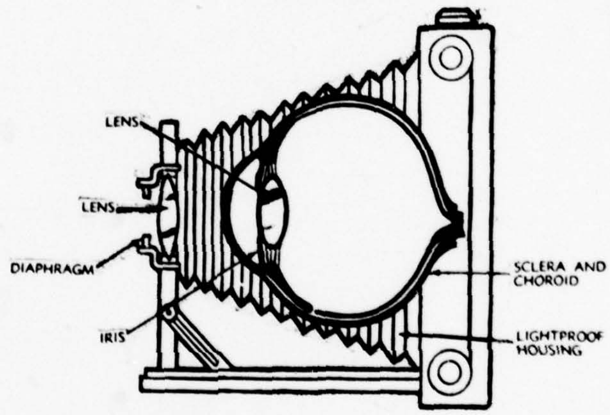


FIGURE 2-3.*,** COMPARISON OF THE EYE AND CAMERA

Refracting Mechanism

The cornea and the lens act together as a convergent lens system to form a real image on the retina of the eye. The cornea is the first refracting surface for light entering the eye and is responsible for about 75 percent of the refracting power of the eye. The cornea is transparent and the refracting power is due to its curvature and refractive index difference between it and air on one side, and the aqueous humor on the other. The two surfaces of the cornea usually are of similar curvature. Changes in focus to adjust the eye for various object distances are made by the lens which changes to make the adjustment. The lens is a transparent elastic body with a less dense outer layer and a denser inside core. The lens changes curvature to focus light from near and far points onto the retina brought about by action of the ciliary muscle changing the tension of the suspensory ligaments. Figure 2-2 shows the ciliary process in detail with the eye focused on a near object in Figure 2-2B, and the eye relaxed and focused on a distant object in Figure 2-2C. The process of changing focus from a near point to a far point is referred to as accommodation, and the normal eye

*,** Ibid, page 2-1

has the ability to focus on an object at a near point of about 5.9 inches and a far point of infinity. This decreases with age, as a result of loss of elasticity of the lens.

Iris Function

Built into the eye is an adjustable diaphragm designed as the iris. As shown in Figure 2-4, it acts as an aperture stop for the lens, just as the diaphragm of a camera does. The iris opens and closes automatically, contracting under very bright light and expanding in dim light. The opening in the center of the iris is called the pupil. The size of the pupil will vary in young eyes from 8mm in dim light to about 2mm in bright light. The iris is composed of radial and circular muscle fibers, over which we have no control. The opening and closing of the iris is an automatic function of the nervous system and it thus tends to hold the illumination on the retina constant regardless of image brightness.

FIGURE 2-4.*,** IRIS AND DIAPHRAGM OF A CAMERA

Vision

Light energy striking the retina of the eye enables us to see, but the optical image formed on the retina is only the starting point of a complicated process of visual perception and visual memory. The fact is that you do not see the retinal image, instead you see with the aid of this image. The incoming light forms a pattern that gives information for the nervous system to pick up. This information is then used by the viewer to guide movements, anticipate events, and construct a mental experience. The visual process is then supplemented by the memory that stores the information in the brain. The retinal images are constantly changing in position, size, the shape as the viewer moves his eyes or the object being viewed is moved. Usually we are not aware of our eye movements as they are moved by the contraction of one or more pairs of opposed muscles triggered by the nervous system. Such eye movements are necessary because the area of clear vision available to the

*,** Ibid, page 2-2

stationary eye is severely limited. To see this, all one needs to do is fixate on a point of some unfamiliar picture or printed page. Only a small region around the fixation point will be clear while most of what is being viewed will be hazily visible. This is due to the structure of the retina and the placement of its sensitive elements. The retina which covers most of the area behind the ciliary process, translates light energy into nervous energy and contains the first coordinating nerve cells in the visual system. The front part facing the lens is composed of blood vessels, nerve cells, nerve fibers, and connective tissues.

Figure 2-1B shows a cross section of the human retina, magnified about 500 times. In this picture, light is coming from the left. The light-sensitive elements are composed of two different kinds of specially developed nerve cells. They are called rods and cones because of their shape. The light-sensitive layer of rods and cones lies behind the retina. Before light can reach that layer, it must pass through several layers of tissue, containing a network of nerve fibers and blood vessels. These layers are extremely thin, so they don't absorb much light. But, they do affect the sharpness of the image. In some of the lower animals, the sensitive layer is at the front of the retina, with the nerve and blood supply behind it. Those animals probably see more clearly than humans. However, the human retina has the advantage that the sensitive layer is in contact with the rich blood supply of the choroid. That helps to keep the efficiency of the retina at a high level over a long period of time.

As illustrated in Figure 2-1, the entrance of the optic nerve is a blind spot where there are no light sensitive cells. The retina thins at the visual axis because there are no blood vessels or nerve fibers over the fovea which is the most sensitive part of the retina. The center of the fovea contains only cones that are longer, thinner, and more densely packed than cones elsewhere in the retina. From here to the edge of the retina the number of cones per unit area decreases and the number of rods increases. The sensitivity of the retina to light varies, and since the fovea is the most sensitive, it is used to see fine detail and color. The cones of the fovea are individually connected to a single nerve fiber and have a direct path into the optic nerve. Because the fovea is highly sensitive and small, we must constantly shift our eyes when looking at an object in fine detail.

Night Vision

Cones appear to be a factor in acute vision, as the eye tends to rotate in order to bring the image nearer to the area where cones are most concentrated. It also appears that the rods in the retina are associated with night vision. Some facts that support these statements are:

- Animals that hunt at night and sleep in the daytime (such as bats) have retinas composed almost entirely of rods.
- Animals that go to sleep as soon as it getsdark (such as pidgeons) have retinas composed almost entirely of cones.
- Human beings who get around both day and night have retinas composed of both.

The structure of the rods and cones is complex and the exact mechanism of vision is not fully known. We do know that the retinal rods contain a red colored photosensitive pigment called rhodospin which is bleached when exposed to light. The product of this bleaching is a stimulation of the nerve cells in the eye making the rods sensitive to very small amounts of light.

The retinal cones contain a violet-colored photosensitive pigment called iodospin that is similar to rhodospin but more capable of undergoing physical change. Even though the cones respond more quickly to light, it takes a greater amount of intensity to trigger this response. An example of the change taking place in the eye is when a person goes from bright sunlight into a darkened room where it takes the eye several minutes to adjust to the lower illumination level. This occurs because the retinal rods, even though they are more sensitive to low illumination, do not respond as quickly as the cones. The reverse procedure holds true when we again emerge from a darkened room into bright sunlight.

Color Vision

White light is a combination of all the wavelengths of the visual spectrum. However, when an object is viewed in color, it is reflecting or emitting waves of a certain wavelength. As an example, red objects reflect wavelengths greater than .640 microns and blue objects reflect wavelengths between .410 and .460 microns.

Aside from the cone cells being less sensitive than the rods, the cones are also the sensitive cells in color vision. This is proven by the fact that at very low levels of illumination all radiation regardless of wavelengths give rise to colorless sensations. The normal human eye can match any color with a mixture of three primary colors; red, green, and blue. The brightness of color in the objects that are seen depends on the radiant energy in the light.

Resolving Power

The resolving power of the eye or an optical system is the ability to distinguish between two adjacent points and is often expressed as the ability to distinguish between small lines and fine angles. Since resolving power is a measure of the ability of an optical system to distinguish fine detail, it is an important property of the system.

Figure 2-5 illustrates what is meant by two adjacent points forming an angle with the eye. The average eye can resolve details subtending one (1) minute of arc. This is brought about by the image falling on the retina and stimulating more than one cone, with a separation of at least one unstimulated cone between them. Therefore, the normal eye can distinguish between two equally bright objects, separated by an angle of one (1) minute.

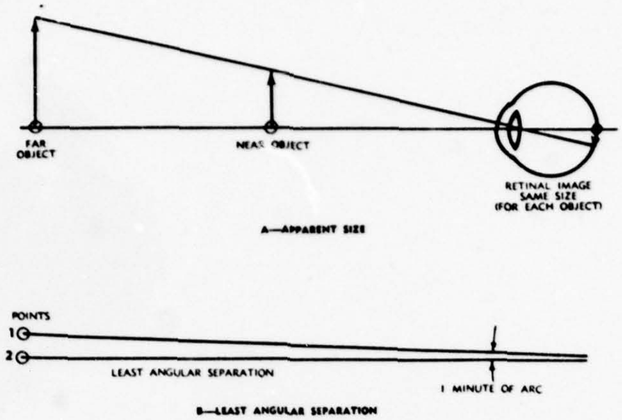


FIGURE 2-5. VISUAL LIMITATIONS

The rods and cones give the retina a mosaic structure that determines resolution where the maximum resolution depends on three factors:

- Retinal location of the image,
- Nature of the image, and
- Adequate time for stimulation.

Retainal location of the image means that the image must fall on the fovea of the retina where vision is most acute. As a result, the resolving power of the eye decreases as the image moves away from the fovea. Nature of the image means its brightness which is the light necessary to stimulate the retina. The smallness of a light or bright spot that can be seen will depend solely on its brightness. Adequate time for stimulation means that an image must fall on the retina long enough to cause stimulation of the nerve cells. For example, bright objects will stimulate quicker than dim objects. All of these factors can be fully realized when viewing at night. If a small but very bright light is seen, the eye experiences a quick stimulation and the light is very noticeable. If a dim light is viewed at night, the eye must concentrate for a much longer period of time in order to discern it.

NATURE OF VISIBILITY

Visibility is one of the most complicated of all meteorological elements. A number of visibility instruments have been developed, but none has been considered sufficiently practical to replace observations made by the unaided eye. The measure of visibility and visual range depends on the lack of transparency of the atmosphere. The lack of transparency of the atmosphere, depends on the amount of foreign particles in the atmosphere, and it affects visibility in the following manner:

- The strength of light traveling through the atmosphere is reduced by absorption and scattering caused by the air molecules and by minute particles of matter suspended in the air. These particles include spores, bacteria, dust, smoke, fog, and ice crystals.
- The amount by which the light is lost or attenuated depends upon the size, kind, and quantity of suspended particles. The color of light that is most scattered or transmitted also depends upon the size, kind, and color of particles in the air at any particular time.
- Air molecules are of such a size that blue light is scattered about ten times more than red light. The sun at sunset is red for the reason that sunlight at sunset must travel through a long path of air. Along this path, the blue portion of the sunlight is scattered in all directions, while the red light remains by the time the direct light reaches the eye at the end of the path.
- Haze, composed of extremely small particles, also scatters blue light more than red, although these colors do not appear as pure in haze as they do when the light is scattered by air molecules.
- The size of fog droplets can vary over a large range. Since the color of light that is most scattered depends upon the size of the particles, it can be expected that different types of fog will scatter colors in different degrees.
- Clean, pure fog droplets smaller than one micron in radius scatter blue light more than red. If the droplets are between about 1.5 and 5 microns in radius, they scatter red light more than blue. Droplets of more than five microns in radius (the most common fog) scatter all colors about equally.
- The amount of attenuation of light depends upon the amount of scattering and absorption of light by the air and other particles in the air. A measure of this ability to scatter and absorb light is the extinction or attenuation coefficient. It is evident that visibility is related to the attenuation coefficient and is inversely proportional to the amount of light absorbed and scattered. Although visibility also depends upon a number of other factors, it is important to understand why an object may be visible or invisible, depending upon the range from the object to the eye.

Daylight Visibility

For an object to be visible, it must be distinguished from its surroundings. In other words, the object must be contrasted with its background. If no contrast were perceptible, we would not be able to distinguish the object from its surroundings and it would be invisible. This is one of the principles applied in camouflage. For purposes of discussing daylight visibility, the principal contrast that enables us to distinguish an object is the contrast in brightness. Brightness is the luminous intensity per unit area normal or perpendicular to the line of sight. The luminous intensity is usually expressed in candlepower, which represents a certain definite rate of flow of light energy. If the difference in brightness between an object and a brighter background is made smaller by increasing the brightness of the

object, a point is finally reached where we no longer can distinguish a difference, but, since our eyes are not perfect instruments, the difference is not apparent to us. Now, if the actual brightnesses of object and background are measured when the object is just visible, their actual contrast can be found. The contrast is calculated on a relative basis by dividing the difference in brightness by the brightness of the background. This contrast is called the threshold of brightness contrast. It is obvious, therefore, since all people's eyes are not the same, this value varies from person to person, within certain limits, and depends also on the adaptation of the eyes to existing light conditions.

The threshold of brightness contrast is related to visibility in the following way. Suppose that a black object is viewed in the daylight against a completely cloudless sky. As the object moves farther and farther away, toward the horizon, it appears to become lighter and lighter, and its apparent brightness becomes more and more the same as that of the sky. Finally, at some distance, the object is no longer visible, because no contrast can be discerned between it and the sky. The reason why the object appears lighter as its distance from the observer increases is easy to understand. Sunbeams from the window, slanting across a room, are made visible by the dust particles in the air. The path seems lighted up. In the same way, though not so spectacularly, since the light is not broken up into separate beams outdoors, the air between an observer and an object is lighted up as the result of scattering. The longer the air path, the more air-light there is between the observer and the object. Thus, the further away the object, the brighter it appears.

It is obvious that, by moving the black object farther and farther toward the horizon, the contrast will diminish until it equals the threshold brightness contrast. At this point the object will just be visible. This distance from the observer to the object is the visibility. This certain distance at which the object becomes visible is related to the attenuation coefficient, which becomes greater as the distance becomes less. As the number of foreign particles in the atmosphere increases, the value of the attenuation coefficient increases, and the visibility decreases.

Factors Which Influence Visibility*

The concept of visibility implies a visible object. It is in the choice of a reference object that our difficulties multiply. We find that visibility depends (apart from individual differences in visual acuity) upon various properties of the object, surroundings, and lighting. These properties include:

- reflecting power and color of the object,
- reflecting power of the background,
- amount of cloudiness,
- position of the sun,
- angular size of the object,
- nature of the terrain between the object and observer, and
- bright light points in the field of view.

* Haynes, B.C. (1947). Techniques of Observing the Weather, John Wiley & Sons, N.Y.

These properties which influence visibility will now be discussed in more detail.

- The Ideal Object and Background. The visibility of a black object against a sky background constitutes the ideal object and background and (with either a cloudless sky or a completely overcast sky) can easily be computed by knowing the attenuation coefficient and the threshold values. The position of the sun in this instance makes no difference.

- Effect of Different Objects and Backgrounds. The numerical examples of Table 2-1 illustrate the effects of different objects and backgrounds on visibility. It is assumed that the same atmospheric conditions prevail, the sky is uniformly overcast, and the objects are of the same angular size.

  This table shows that: (1) gray objects may be used, but they should be as dark as possible, (2) white objects should not be used, and (3) the sky should be the background for the objects.

TABLE 2-1*

EFFECTS OF OBJECTS AND BACKGROUNDS ON VISIBILITY

Object	Background	Visibility Miles
Black	Sky	3.0
Gray (reflecting 15% light)	Sky	2.9
White	Sky	2.5
Black	Snow	2.3
Gray (reflecting 15 % light)	Snow	2.1
Black	Ground	0.9

- Position of Sun. The above points are further emphasized when we consider the effect of the position of the sun relative to the observer and object. Table 2-2 illustrates the effects of sun position on visibility. The sky is assumed to be clear, and the sun is at an elevation of 20°.

TABLE 2-2*

EFFECTS OF SUN POSITION ON VISIBILITY

		Visibility, Miles		
Object	Background	Sun Before Observer	Sun Directly to Right or Left of Observer	Sun Behind Observer
Black	Sky	3.00	3.00	3.00
Gray (reflecting 15% light)	Sky	2.97	2.97	2.43
Black	Ground	0.72	1.11	2.91
Gray (reflecting 15% light)	Ground	0.36	0.63	2.22

*Ibid, page 2-9

- Color of Objects. If the objects are colored the situation becomes more complex. However, if the colored objects are not too bright, they will behave about the same as gray objects. This is rather significant since dark-colored buildings (dark red brick, etc.) may be used as reference objects, always keeping in mind what has been said about the background and the object size. As the distance of a colored object approaches the limit for visibility, its color seems to disappear and it looks gray, so it may be treated as a gray object. Table 2-3 shows the effects of color on visibility under the same atmospheric conditions, but using objects of different colors as reference points. It illustrates the fact that the colored object acts nearly the same as a gray object with the same reflecting power.

TABLE 2-3*

EFFECTS OF COLOR ON VISIBILITY

Color	Reflecting Power, %	Visibility, Miles
Gray	13	9.18
Red	13	9.10
Gray	30	8.95
Blue-green	30	9.05

- Angular Size of Objects. The angular size of objects is the angle subtended by the object at the oberver's eye as shown in Figure 2-6.

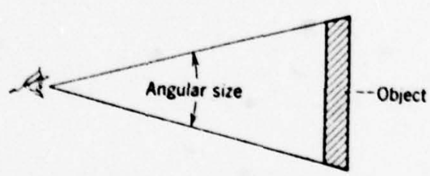


FIGURE 2-6.* ANGULAR SIZE OF OBJECTS

For objects subtending angles less than 1°, the visibility decreases rapidly as the angle becomes smaller. Above one degree to about five degrees, there is very little variation in visibility as shown in Figure 2-7, in which the angle subtended by the object is plotted against visibility.

For example, Figure 2-7 shows that if an object subtending 3° is just visible at three (3) miles, then, under the same conditions an object subtending only 0.3° could not be seen beyond 1.6 miles.

*Ibid, page 2-9

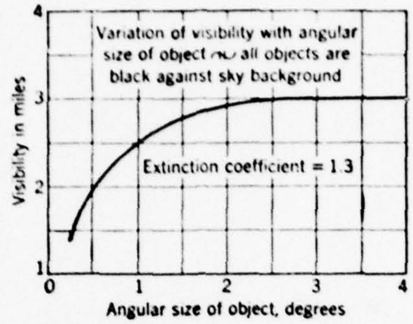


FIGURE 2-7.* ANGULAR SIZE OF OBJECTS VS. VISIBILITY IN MILES

- Effect of a Bright Light in the Field of View. The dazzling effect of looking toward a bright light is a common experience. If such a source is close to the line of sight, the object being sighted is more difficult to see. The visual range will appear less than it actually is, because the threshold brightness contrast increases owing to the dazzling effect in the eye. Observers unconsciously correct somewhat for this by shading their eyes with their hands when determining visibility in directions near the sun.

- Effect of Terrain Between Observer and Object. If the terrain between the observer and the object is highly reflective (such as lakes, white sand, or snow) there will be an appreciable addition of air-light in the space between observer and object, causing the object to be less visible than it would be if the intervening terrain were dark soil or grass.

- Effects of Moonlight, Starlight, and Twilight. The visual range of objects in the subdued light of moonlight, starlight, or twilight is less than in daylight. The reason is obvious. As an example of the magnitude of this effect, suppose that the visibility were such as to permit an object to be just visibile at 2 1/2 miles in daylight; in bright moonlight the object would not be visible at more than about 0.6 miles. In twilight the same sort of effect is noticeable. However, in twilight the illumination and the brightness of the sky vary with direction, so that the visibility will depend on the direction of the object.

Visibility at Night*

Visibility at night, of necessity, is determined mostly by the visual range of lights rather than by objects. Therefore, only unfocused beams and beacons can naturally be seen farther than ordinary lights. It is evident that, since the distance at which lights can be seen depends upon their candlepower, this distance has no relation to the visibility determined by objects in the daytime. Candlepower is the amount of light per unit spherical angle. If the proper candlepower lamp is chosen, there will be a 1:1 correspondence between the visibility determined in daylight and the visibility determined at night by means of the lamp. Thus, under similar conditions, when the visibility in daylight is three miles, it would take a 225-candlepower lamp to be just visible at three miles at night.

* Ibid, page 2-9

In the discussions which follow, for the sake of clearness, visual range will be defined as the distance at which a dark object subtending $2^{\circ} - 3^{\circ}$ is just visible against the horizon sky, during daylight. The distance at which an electric lamp is just visible at night will be called lamp range.

- Variation of Lamp Range With Candlepower. The candlepower is not only dependent upon the design of the lamp and the direction in which it is turned but also upon the voltage impressed upon it. For example, suppose that the visual range were three miles; then a 60-candlepower lamp would be just visible at 2.3 miles at night (lamp range). Now suppose that the voltage of 110 volts is reduced by 18 percent. The lamp would now be giving only about 31 candlepower and the lamp range would be two miles. If the voltage had increased by 18 percent, the lamp would give about 106 candlepower and the lamp range would be 2.6 miles. In the foregoing example, the transparency of the atmosphere was held constant, so that the visual range would have been three miles. Suppose now that the atmosphere becomes clearer, giving a visual range of 10 miles. What would be the behavior of our lamp range? At 60 candlepower, the lamp would be just visible at 4.6 miles. If the voltage to the lamp were reduced by 18 percent, the lamp would then be visible at distances no greater than 3.8 miles. If the voltage increased by 18 percent, the lamp range would be 5.2 miles. Not only, therefore, are most lamp ranges different from the visual range under the same atmospheric conditions, but changes in line voltage cause changes in lamp range. Thus, considering only lamps of ordinary candlepower, for poor visual range, changes in line voltage have only small (perhaps negligible) effects while for good visual ranges the effect is greater. Also, for poor visual ranges the differences between visual range and lamp range is less than for good visual range. Suppose, however, that we use a much stronger lamp, say one of 750 candlepower, at a voltage of 110. If the visual range were 10 miles, this lamp would be (under the same atmospheric conditions) just visible at night at eight miles. If the voltage dropped by 18 percent, the lamp range would be about seven miles. If the voltage increased by 18 percent, the lamp range would be about nine miles. Now if the atmospheric conditions were such that the visual range is but 3/4 mile, and a 750-candlepower lamp at 110 volts were used, the range would be about 1.4 miles. If the voltage dropped by 18 percent, the lamp range would be only about 1.2 miles. However, if the voltage increased by 18 percent, lamp range would still be no more than 1.4 miles. It is thus evident that, if a system of lamps is to be used for determining lamp ranges, and their voltage is not kept constant, lamps of high candlepower are better than lamps of low candlepower. Table 2-4 shows the approximate relationships between the various factors already discussed.

TABLE 2-4 *

VISUAL RANGE VS LAMP CANDLEPOWER

Visual Range, miles	Candlepower at 110 volts = 60 candlepower Distance Lamp Is Visible At Voltages of 90	110	130	Candlepower at 110 volts = 100 candlepower Distance Lamp Is Visible At Voltages of 90	110	130	Candelepower at 110 volts = 750 candlepower Distance Lamp Is Visible At Voltages of 90	110	130
3/4	0.9	0.9	1.0	0.9	1.0	1.1	1.2	1.4	1.4
3	2.0	2.3	2.6	2.2	2.6	2.9	3.3	3.6	4.0
6	3.0	3.5	4.0	3.4	4.0	4.4	5.2	5.8	6.4
10	3.8	4.6	5.2	4.4	5.2	6.0	7.0	8.1	9.0

- Flashing Lights. The visual range of flashing lights may, for practical purposes, be considered the same as that for steady light, as long as the duration of each flash is several seconds. If, however, the flashes last for much less than 0.2 second, the light will not be visible as far as a steady light. As an example, suppose that a certain steady light is visible at 3 1/2 miles; then if the same light were to flash on and off so that each flash on lasts only 0.02 second, the light would be visible at only two (2) miles. Since flashing lights of such small intervals are rarely used in practice, this consideration may be ignored with respect to visibility determinations.

- Effect of the Brightness of the Background of Lamps. If a white lamp is seen against a background that is not black but has a certain brightness, the lamp cannot be seen as far as it could be if it were against a black background. To illustrate this, assume that the visual range is three (3) miles. A lamp of 225 candlepower, against a black background, can be seen at three (3) miles. A similar lamp against a background of moonlit snow, would have to be at about 2.8 miles to be visible. Evidently, then, at least for lower visibilities, the effect is not very important. If we examine the situation for longer visibilities (say 10 miles), a lamp which can be seen at eight miles against a black background would have to be moved to about 7.6 miles to be visible against moonlit snow. Again it appears that the difference in the visual range of the lamp is not of too great magnitude. For red lamps, within reasonable limits, the background brightness has no effect.

- Effect of Fog. The preceding discussions were based on night visibility conditions of over 1/2 mile and in the absence of fog. If fog exists, the lights no longer act as point sources. The fog particles scatter the light and form a large luminous area surrounding the lamp. The light from this luminous area is diffused light. According to several sources, the eye is 7,000 to 170,000 times more sensitive to light from a point source than to diffuse light,

* Ibid, page 2-9

depending upon background brightness. Therefore the diffused light caused by the fog around a lamp cannot be seen as far as the light from the same lamp not surrounded by fog. To illustrate the relative sensitivity of the eye to point and diffuse sources, consider and compare the candlepower necessary to make a flash from a point source (a lamp), and light reflected from a cloud visible at six (6) miles. For the point source if a candlepower of 250 is sufficient, then nearly 3,250,000 candlepower will be necessary for light reflected from a cloud.

- Effect of color. The effect of color of a light source on visibility is substantially the same in fog as in clear air. Red lights, including neon, of the same candlepower as white lights cannot be seen any farther than the white lights in a fog. For this reason it is satisfactory to use red obstruction lights as visibility markers.

Estimating Visibility

In estimating visibility, there are situations where the observer may be so located that the farthest visible objects on all horizons are so close that true visual range may not be obtained for conditions of excellent visibility. Under these conditions, the observer should estimate the visibility by noting the transparency of the atmosphere. Small objects should be observed, and their sharpness may serve as a guide for selecting the visibility. When the more distant objects stand out sharply with little blurring of color, the air may be considered free of haze and the visibility quite high. If the objects are blurred or indistinct and seem to have a gray or purplish hue, it indicates the presence of haze or other obstructions and a reduced visibility can be expected.

ATMOSPHERIC EFFECTS ON DETECTION RANGES *

In the preceding section, the eye has been considered as a detecting instrument operating on targets of given apparent size, contrast, and shape. Before these results can be applied to an actual case or operation, it is necessary to find how the circumstances of the case determined these variables and hence, indirectly, the probabilities of detection. Now in any actual case, certain intrinsic characteristics of the target may be regarded as known. These are its geometrical shape and dimensions and diffuse reflecting power. Except within small angular distances from the sun, the latter determines the intrinsic brightness of the target in units of sky brightness. The intrinsic characteristics of the immediate and general background and the relationships between all intrinsic and apparent quantities are determined by the circumstances of the case. The study of these various dependences and relations is the subject of this section.

* Douglas, C.A., and Booker, R.L. (1977). Visual Range: Concepts, Instrumental Determination and Aviation Applications. Optical Physics Division, National Bureau of Standards, NBS Monograph 159, U.S. Dept. of Commerce

Brightness

The presence of material in the atmosphere alters the pattern of light received by the eye from the various points of the target and background and acts to,

- remove some of the light by absorption and scattering out of the line of sight, and
- add some light reaching the eye from the direction in which the observer is looking by scattering into the line of sight.

The basic expression for the apparent brightness of the target viewed against the horizon sky is,

$$B_R = B_o e^{-\beta R} + B_S (1 - e^{-\beta R}), \tag{2-1}$$

where,

B_R = apparent brightness of the object at range R,

B_o = intrinsic brightness of the object,

β = attenuation coefficient,

$e^{-\beta}$ = T (transmissivity),

$\beta = \beta_{sc} + \beta_{ab}$

β_{sc} = scattering coefficient,

β_{ab} = absorption coefficient,

R = range from detector to object, and

B_s = brightness of the horizon sky in the direction of view.

This basic relation will be used in determining the visual range of objects. The first term represents the direct attenuation of the intrinsic brightness of the object by scattering and absorption. The second term represents the additional contribution to the apparent brightness of the object due to external illumination from all directions that is scattered into the observers eye by the material in the atmosphere.

Similarly, the apparent brightness of the background immediately surrounding the target is,

$$B_{AB} = B_b e^{-\beta R} + B_s (1 - e^{-\beta R}). \tag{2-2}$$

where, B_{AB} = apparent brightness of the background, and

B_b = intrinsic brightness of the background.

Therefore, the difference in brightness between object and immediate background is,

$$B_R - B_{AB} = (B_o - B_b)\, e^{-\beta R}. \qquad (2\text{-}3)$$

Contrast *

The apparent contrast is the ratio of this brightness difference and the effective background brightness. There are two main cases which arise in actual operations, one in which the immediate background and the effective background are the same and one in which they are different. The first case is exemplified by search for an object silhouetted against the sky. The second case is exemplified by search for a target on land. In this case, the line of sight frequently approaches the horizon so that the adaptation of the eye is determined partly by the brightness of the land and partly by that of the sky. Because light adaptation is rapid compared to dark adaptation, the bright sky is responsible, almost entirely, for setting the level of response of the eye. Therefore, in both cases, the sky brightness is a reasonable approximation to the effective background brightness and the object contrast can be expressed as,

$$C_R = C_o e^{-\beta R}, \qquad (2\text{-}4)$$

where,

C_R = contrast of the object at range R,

C_o = intrinsic contrast of the object, and

$C_o = \dfrac{B_o - B_b}{B_b}$ (see Section 1),

Visual and Meteorological Ranges *

The concepts of visual and meteorological ranges are derived from the ideas of contrast attenuation and visual threshold. Both concepts refer to the wavelength at which the eye has the greatest sensitivity which is at .550 microns. Visual range can be defined as the distance, under daylight conditions, at which the apparent contrast between a specified type of target and its background (horizon sky) becomes just equal to the threshold contrast of an observer. The visual range is a function of atmospheric attenuation, albedo (reflectance), visual angle of the target, and the observer's threshold contrast at the moment of observation. Values of visual range usually are estimated from the appearance of buildings and special targets at differing distances against the skyline. The expression for visual range is,

$$V = \frac{1}{\beta} \ln \frac{C_o}{C_t}, \qquad (2\text{-}5)$$

where,

V = visual range, and

C_t = contrast threshold or the contrast at which an object is just visible against its background.

* Cwalinski, R. et al, Field Testing and Evaluation of Methods for Measuring Visibility, NW Environmental Tech. Labs., Bellevue, Wash., NTIS, PB-215-548/4sT

It is apparent from Equation (2-5) that the visual range of an object is determined by the inherent contrast of an object, C_o, the attenuation coefficient, β, and the contrast threshold, C_t. There are methods for measuring β while values for contrast threshold C_t can be estimated. There is no feasible way of determining C_o except by direct measurement of B_o and B_b. Moreover, except for black objects, C_o is not constant but will vary with the extent of cloud cover and with the position of the sun with respect to the object. The subjective factors and optional target features involved in the strict meaning of visual range are not present in the meteorological range. This is obtained by specifying a black or dark object and letting C_t = 0.02. In practice, the object is made large enough so that this value of C_t is applicable. Since the target is black, its inherent contrast against the sky is unity and equation 2-5 becomes,

$$V_M = \frac{(-\ln C_t)}{\beta} = \frac{3.912}{\beta} \qquad (2\text{-}6)$$

where,

V_M = meteorological range which is the maximum distance at which large dark or black objects, such as mountains and buildings, can be seen against the sky,

C_t = 0.02 for a black or very dark large object, and

C_o = 1 for a black or very dark large object.

Equation (2-6) shows that the visual range of a large black object is independent of the brightness of the background sky and the direction of view with respect to the sun. This is the reason that black or very dark objects are chosen as visual markers for observation. If we now substitute Equation (2-6) into Equation (2-5), we obtain,

$$V = \frac{V_M}{3.912} \ln \frac{C_o}{C_t} \qquad (2\text{-}7)$$

Where the visual range is now dependent on the meteorological visibility and not on the attenuation coefficient. This turns out to be a very useful expression because it is not dependent on the attenuation coefficient. This concept of using large black objects as reference visual ranges will be utilized even further in the following section.

Visibility Factor and Contrast Threshold Criteria

Although variation in contrast is not a significant factor in determining the accuracy of routine meteorological observations, the effect of contrast on visual range is of interest because the visual range of many objects which are not black is of interest. The visibility factor is the ratio of the visual range of a large object to the visual range of a large black object and is expressed as follows using Equation (2-5):

$$K = \frac{V_o}{V_{BL}} = \frac{\frac{1}{\beta}\ \ln\ \frac{C_o}{C_t}}{\frac{1}{\beta}\ \ln\ \frac{C_{BL}}{C_t}} = 1 - \frac{\ln C_o}{\ln C_t}, \qquad (2\text{-}8)$$

where,

K = visibility factor,

V_o = visual range on a large object,

V_{BL} = visual range on a large black object,

C_o = contrast of large object, and

C_{BL} = contrast of large black object = 1.

Figure 2-8 indicates the relationship between the visibility factor and the intrinsic contrast of the large object for a contrast threshold, $C_t = 0.05$. The intrinsic contrast of the object ranges from zero for a grey object so lighted by daylight that it blends with the sky to as high as five for a white object in direct sunlight.

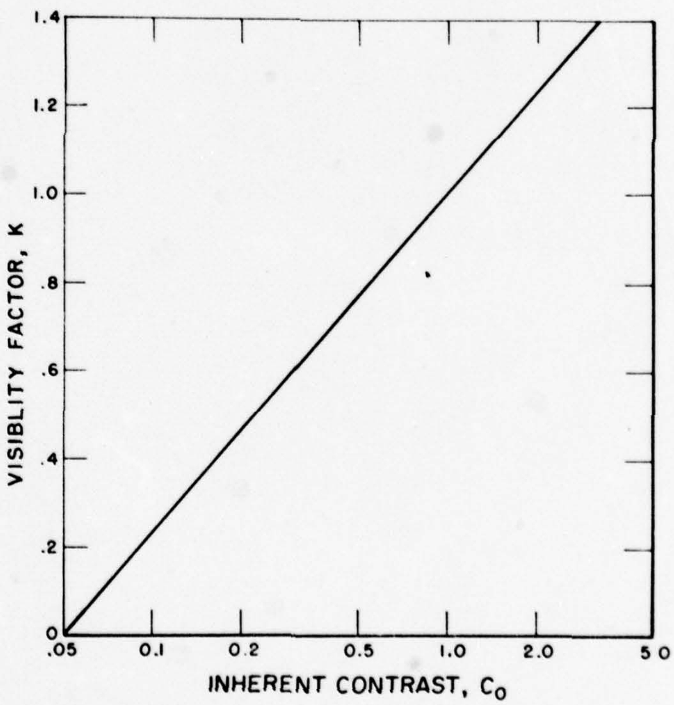


FIGURE 2-8.* EFFECTS OF INHERENT CONTRAST UPON VISIBILITY FACTOR. $K = 1$ WHEN $C_o = 1$. A CONTRAST THRESHOLD OF 0.05 IS ASSUMED.

* Ibid, page 2-15

The apparent contrast and the visual range of an object viewed horizontally against a background other than the sky may be determined by using Equation (2-1). For objects viewed against an immediate terrestrial background the following equation applies:

$$C_t = C_o \left(1 + (B_s/B_b)(e^{-\beta V_o} - 1)\right)^{-1} \tag{2-9}$$

where,

C_t = contrast threshold of the object,

C_o = intrinsic contrast between the object and its background,

B_s = brightness of the sky in the direction making the same angle at the object with the line of sight as it does with a line from the object to the sun,

B_b = brightness of the background of the object, and

V_o = visual range of the object.

In this situation, the apparent contrast, and therefore, the distance an object can be seen, depends on the direction of view, the brightness of a particular section of the sky, the inherent brightness of the background, and the contrast between the object and its background. When the line of sight is horizontal, B_s is the brightness of the portion of the sky directly behind the object and its background. The visibility factor is obtained by combining Equations (2-9) and (2-6) and results in the following:

$$K = \frac{\ln\left(1 - (B_b/B_s)(1 - C_o/C_t)\right)}{\ln(1/C_t)} \tag{2-10}$$

This expression is plotted in Figure 2-9 where a value of 0.05 was used for the contrast threshold, C_t. Figure 2-9 can be more easily understood by considering the following situations. The ratio B_b/B_s varies from about five or more on a sunny day with a snow background to less than 0.01 in directions near a low sun shining through a haze with a grass background. In the case of a grass background on an overcast day, the ratio will be about 0.2 to 0.3. On hazy days, with the sun visible through the haze, the ratio may vary over a range of more than 10 to 1 around the horizon. Contrasts between natural objects and their backgrounds may be as low as 0.2. The conditions for values of B_b/B_s greater than five are not common and usually require, in order to simultaneously produce both a high contrast and a high value for the ratio B_b/B_s, that sunlight be specularly reflected from the object. Therefore, in general, the visibility factor will be less than one, ranging from 0.3 to 0.6 under overcast daylight conditions to less than 0.1 with a low sun shining through haze. The development of the theory of the visibility of objects given above has been simplified in the interest of brevity and clarity. A uniform atmosphere with a constant attenuation coefficient has been assumed. Field experience has indicated that the equations developed above are sufficiently general to represent the visual range of objects in practical applications.

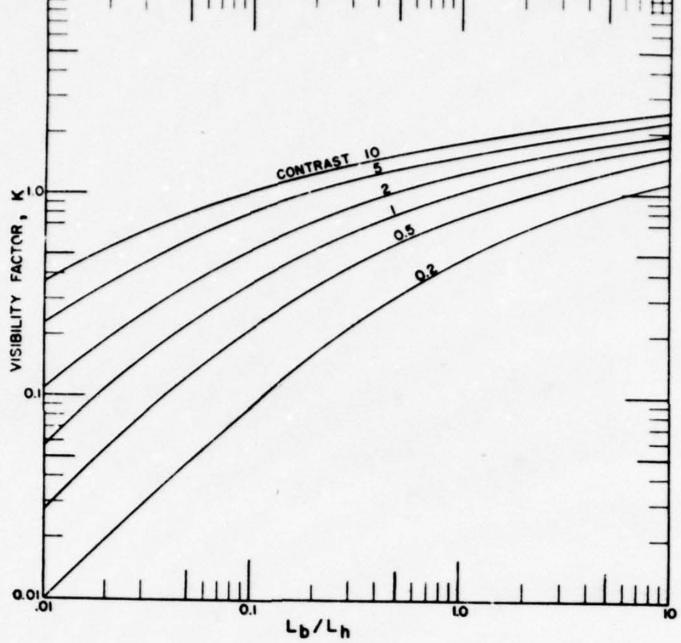


FIGURE 2-9.* EFFECTS OF GROUND/HORIZON SKY LUMINANCE RATIO AND CONTRAST ON VISIBILITY FACTOR FOR OBJECTS WITH A TERRESTRIAL BACKGROUND, BASED UPON A CONTRAST THRESHOLD OF 0.05.

The values used for contrast threshold normally range between 0.02 and 0.06. Usually, the visual range is not very sensitive to a change in contrast threshold since the relationship is logarithmic. However, some criteria for contrast threshold is required. This general criteria is as follows:

- Use a value of $C_t = 0.02$ for large black objects.
- Use a value of $C_t = 0.05$ for a trained, professional observer.
- Use a value of $C_t = 0.035$ when general field conditions are assumed and different types of observers are used.

It should be pointed out that the Federal Aviation Administration (FAA), currently uses the value $C_t = 0.055$ as the basis for the definition of a daylight visual range. However, the value $C_t = 0.02$ still persists in the definition of meteorological range.

Nighttime Visual Range

Nighttime visual range cannot be stated in terms of how far a dark object can be seen against the horizon sky but is stated in terms of the distance at which a high intensity source can just be seen. The governing law was given by Allard.**

*Ibid, page 2-15
**Allard, E., Memoire Sur l'intensite Et La Portee Des Phases, Paris, Punod, 1876.

$$E_R = \frac{Ie^{-\beta R}}{R^2} \qquad (2\text{-}11)$$

where,

E_R = illuminance at range R,

I = intensity of light source, and

R = range.

The concern is not in regard to the contrast threshold of the human eye (as during daylight) but to the illuminance threshold or the minimum amount of light falling on the eye which produces a recognizable sensation of brightness.

Standard Daytime and Nighttime Visual Ranges

Equations (2-6) and (2-11) will be combined with the recommendations of the FAA to obtain the standard daytime and nighttime visual ranges. The FAA standard value of C_t = 0.055 is used as the basis for the definition of daylight visual range. Substituting this value in Equation (2-6) results in:

$$V_{d\ (FAA)} = \frac{2.9}{\beta} \qquad (2\text{-}12)$$

Again, adopting the FAA recommendations, the nighttime threshold illuminance is taken as 2 mile-candles ($E = 7.17 \times 10^{-8}$ lumens ft^{-2}) and the standard light intensity is taken as 10,000 candelas (I = 10,000 candelas). Substituting these values into Equation (2-11) and letting the range equal the nighttime visual range ($R = V_N$),

$$25.43 = 2 \ln V_{N(FAA)} + \beta V_{N(FAA)} \qquad (2\text{-}13)$$

Comparing Equations (2-12) and (2-13) illustrates the condition that, given the same atmospheric conditions with a specific β, it is easier to see a bright light at night than a dark object by day. Therefore, within the conditions of the accepted FAA day and night visual range standards and for a given value of β, the nighttime visual range is greater than the daytime visual range.

Furthermore, it is recognized that, even during daytime, under excessively turbid conditions, the 10,000 candela light source can be seen at greater distances than can the dark object used as the usual reference for the specification of daytime visual range. As a result, the FAA has specified the value of 1000 mile-candles ($E = 3.58 \times 10^{-5}$ lumen ft^{-2}) as the illuminance threshold. Using this value along with I = 10,000 candelas in Equation (2-11) results in the following daytime visual range relative to the distance the high intensity light source can be seen:

$$19.45 = 2\ln V_{D\ (FAA)} + \beta V_{D\ (FAA)} \qquad (2\text{-}14)$$

Figure 2-10 illustrates the standard daytime and nighttime visual ranges using Equations (2-12), (2-13), and (2-14) and also shows the meteorological range of Equation (2-6). The daytime curve combines the visual ranges on a standard light source (for ranges greater than about 4000 feet) and on a dark object (for ranges less than about 4000 feet). It should be emphasized that these standard visual range curves are based on the visual range standards as defined by the FAA. Therefore, these curves form the basis for interpreting all available visual range data from airport operations in terms of the optical quality of the atmosphere.

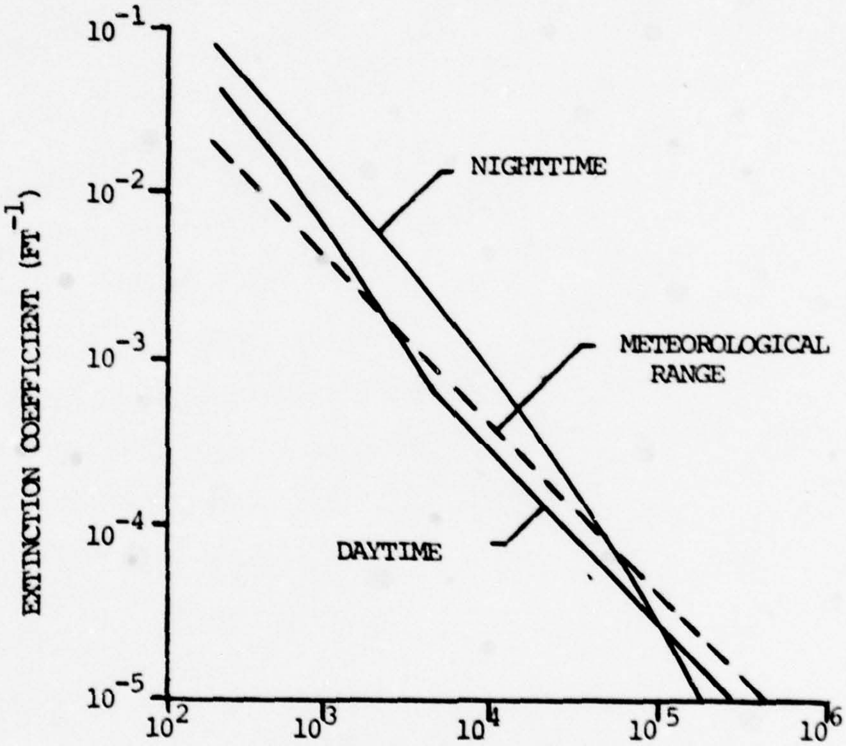


FIGURE 2-10.* VISUAL RANGES ACCORDING TO FAA VISUAL RANGE STANDARDS

Comparing Equations (2-12) and (2-14) and their respective curves shows under what daylight conditions it is easier to see the light source than the dark object. At a visual range of about 4000 feet, both equations yield the same β. Therefore, in clean atmospheres ($\beta < 7.25 \times 10^{-4} ft^{-1}$) a dark object against the horizon sky can be seen and recognized at greater distances than the bright light. When $\beta > 7.25 \times 10^{-4} ft^{-1}$ then the bright light can be seen and recognized at greater distances than the dark object. This fact is recognized by the FAA in airport operations and when the daytime visual range on a dark object against the horizon drops to 4000 feet, the high intensity runway lights are turned on as an aid to air traffic movement and daytime visual ranges are subsequently specified relative to the distance at which those lights can be seen.

* Ibid, page 2-15

3. OBSTRUCTIONS TO VISIBILITY

DESCRIPTIONS OF OBSTRUCTIONS TO VISIBILITY *,**,***

This section will address those obstructions to visibility listed in the Federal Meteorological Handbook on Surface Observations*** and summarized in Table 3-1. Descriptions of these obstructions to visibility are as follows:

TABLE 3-1

OBSTRUCTIONS TO VISIBILITY

OBSTRUCTION	SYMBOL
Fog	F
Ground Fog	GF
Ice Fog	IF
Haze	H
Smoke	K
Dust	D
Blowing Snow	BS
Blowing Sand	BN
Blowing Dust	BD
Blowing Spray	BY

Fog

Fog is the presence of minute water droplets suspended in the atmosphere thereby reducing the visibility range. Moderate, heavy, and very heavy fog conditions can be expected to hide more than half of the sky or extend upward into layers of existing or low clouds. Fog can be classified according to the intensities in Table 3.2.

TABLE 3-2

FOG INTENSITIES AND VISIBILITY

FOG INTENSITIES	VISIBILITY (Miles)
Very Heavy	0 - 1/8
Heavy	1/8 - 1/4
Moderate	1/4 - 3/4
Light	3/4 - 4
Trace	4 - 6

* Kraght, Peter E. (1942). Meteorology for Ship and Aircraft Operation, Cornell Maritime Press, N.Y.

** Haynes, B.C. (1947). Techniques of Observing the Weather, John Wiley & Sons, N.Y.

*** Federal Meteorological Handbook No. 1, Surface Observations, Change No. 3, U.S. Depts. of Commerce, Defense, Transportation, 1 July 1975.

Ground Fog

Ground Fog is a visible aggregate of minute particles of water based at the earth's surface that reduces visibility. This is ground fog if it does not classify as fog. Ground fog is termed shallow when it is less than six feet in depth and does not restrict horizontal visibility. The intensities for ground fog are the same as for fog.

Ice Fog

Ice Fog is a suspension of numerous minute ice crystals in the air, based at the earth's surface, which reduces visibility. Unlike fog, ice fog does not produce rime or glaze on cold exposed objects. Temperatures are usually at or below -20 degrees Fahrenheit when ice fog forms. However, a mixture of liquid and ice fog occasionally forms at temperatures below freezing. This condition may persist for a few hours as the fog changes to ice fog and dissipates due to a drying of the air, even though temperatures continue to fall. Optical effects similar to those associated with ice prisms are observed in ice fog. Temperature-dew point differences may approach eight degrees Fahrenheit or more. The intensities of ice fog are classified the same as for fog.

Haze

Haze is a suspension in the air of extremely small particles invisible to the naked eye and sufficiently numerous to give air an opalescent appearance. This phenomenon resembles a uniform veil over the landscape that subdues all colors. Dark objects viewed through this veil tend to have a bluish tinge while bright objects, such as the sun or distant lights, tend to have a dirty yellow or reddish hue.

- Dry Haze. Dry haze is comprised of dust or salt particles which are dry and so extremely small that they cannot be felt or discovered individually by the unaided eye. However, they diminish the visibility and give a characteristic smoky (hazy and opalescent) appearance to the air. These particles produce a uniform veil over the landscape and subdue its colors. The veil has a bluish tinge when viewed against a dark background such as a mountain, but it has a dirty yellow or orange tinge against a bright background, such as the sun, clouds at the horizon, or snow-capped mountain peaks. This distinguishes dry haze from grayish light fog. When the sun is well up in the sky, its light may have a peculiar silvery tinge due to haze. Irregular differences in air temperature may cause a shimmering veil over the landscape that is called optical haze.

- Damp Haze. Damp haze is composed of microscopically small water droplets or very hygroscopic particles suspended in the atmosphere. Damp haze is similar to a very thin fog, but the droplets or particles are smaller and more scattered than in light fog. Damp haze is usually distinguished from dry haze by its grayish color, the greasy appearance of clouds seen through damp haze as though viewed through

a dirty window pane, and the generally high relative humidity. It is commonly observed on seacoasts, and in southern states, most frequently with onshore winds and in the vicinity of tropical disturbances. A common mode of formation of damp haze is the carrying up to high levels of particles from salt-water spray in windy weather. In contrast, light fog is more commonly observed when there is little movement of the surface air.

Haze can be classified according to the intensities in Table 3-3.

TABLE 3-3
HAZE INTENSITIES AND VISIBILITY

HAZE INTENSITIES	VISIBILITY (miles)
Heavy	1 - 2 1/2
Moderate	2 1/2- 6
Light	6 - 10
Trace	10 - 50

Smoke

Smoke is a suspension in the air of small particles produced by combustion. This phenomena may be present either near the earth's surface or in the free atmosphere. When viewed through smoke, the disk of the sun at sunrise and sunset appears very red. The disk may have an orange tinge when the sun is above the horizon. Evenly distributed smoke from distant sources generally has a light grayish or bluish appearance. A transition to haze may occur when smoke particles have traveled distances of 25 miles or more, when the larger particles have settled out, and the remaining particles have become widely scattered through the atmosphere. Smoke is classified according to the intensities in Table 3-4.

TABLE 3-4
SMOKE INTENSITIES AND VISIBILITY

SMOKE INTENSITIES	VISIBILITY (miles)
Very Heavy	0 - 1/8
Heavy	1/8 - 3/4
Moderate	3/4 - 1 1/2
Light	1 1/2 - 6
Very Light	6 - 10
Trace	10 - 20

Dust

Dust is composed of fine particles suspended in the air by a dust storm or sandstorm. Dust present in the upper air from great distances may give a grayish appearance to the sky and reduce its blueness. Occasionally, the dust aloft may be of a brownish or yellowish hue. Dust is classified according to the intensities in Table 3-5.

TABLE 3-5

DUST INTENSITIES AND VISIBILITY

DUST INTENSITIES	VISIBILITY (miles)
Very Heavy	0 - 1/8
Heavy	1/8 - 3/4
Moderate	3/4 - 1 1/2
Light	1 1/2 - 6
Very Light	6 - 10
Trace	10 - 50

Blowing and Drifting Snow

Blowing and drifting snow are snow particles raised from the ground by a strong turbulent wind.

- Blowing Snow. Snow particles raised and stirred violently by the wind to moderate or great heights. Visibility is generally poor and the sky may become obscured when the particles are raised to great heights. The snow is normally carried so high up from the ground that the vertical visibility is considerably reduced.

- Drifting Snow. Snow particles raised by the wind to small heights above the ground. Visibility is not severely reduced at eye level although obstructions below this level may be hidden by the particles moving nearly horizontal to the ground. This occurs because the snow is drifting so low above the ground that the vertical visibility is not appreciably diminished.

Blowing and drifting snow are classified according to the intensities in Table 3-6.

TABLE 3-6

BLOWING AND DRIFTING SNOW INTENSITIES AND VISIBILITY

BLOWING AND DRIFTING SNOW INTENSITIES	VISIBILITY (miles)
Heavy	0 - 1/4
Moderate	1/4 - 3/4
Light	3/4 - 1 1/2
Trace	1 1/2 - 2 1/2

Blowing Dust and Sand

Blowing dust and sand are particles raised by the wind such that visibilities are reduced. Table 3-7 indicates the intensities and visibility for different blowing dust and sand conditions.

TABLE 3-7

BLOWING DUST AND SAND INTENSITIES AND VISIBILITY

BLOWING DUST AND SAND INTENSITIES	VISIBILITY (miles)
Very Heavy	0 - 1/8
Heavy	1/8 - 3/4
Moderate	3/4 - 1 1/2
Light	1 1/2 - 6
Very Light	6 - 10
Trace	10 - 50

Spray and Blowing Spray

Spray and blowing spray are water droplets torn by the wind from a substantial body of water, generally from the crests of waves, and carried a short distance into the air. The intensities of spray and blowing spray and the effect on visibility are given in Table 3-8.

TABLE 3-8

SPRAY AND BLOWING SPRAY INTENSITIES AND VISIBILITY

SPRAY AND BLOWING SPRAY INTENSITIES	VISIBILITY (miles)
Heavy	1/2 - 2 1/2
Moderate	2 1/2 - 6
Light	6 - 20
Very Light	20 - 50

Drizzle, Rain, and Snow

Drizzle, rain, and snow are precipitation forms that are composed of particles falling from clouds. Precipitation can generally be classed according to those forms that fall in showers (continuously) or never fall in showers. Although there are precipitation forms other than drizzle, rain, and snow (sleet, hail, ice crystals), this section will only describe these most common forms of precipitation.

- Drizzle. This type of precipitation does not fall in showers. It is a rather uniform precipitation consisting exclusively of minute and very numerous drops of water (diameter less than 0.02 inch) which seem almost to float in the air, and visibly follow even slight motions of the air. Drizzle usually falls out of low, rather continuous and thick layer of stratus clouds which may even touch the earth. In cold weather the layer may be thin. It is not to be confused with the very small but scattered droplets which fall at the foremost edge of a general rain area or with light rain. Drizzle does not usually occur with showery weather. When showers do occur during drizzle they are the result of instability above or below the warm, moist layer where the drizzle is forming. Therefore, even the finest rain from shower clouds is not to be confused with drizzle. Along west coasts and particularly in mountains, drizzle may sometimes produce considerable amounts of precipitation, as much as 0.04 inch per hour. Drizzle is normally associated with fog since the two often occur simultaneously. Therefore, drizzle is characteristically accompanied by poor visibility, and this criterion should be used in distinguishing it from fine rain. Drizzle most commonly occurs when a relatively warm, moist layer of air flows over a cooler surface layer of air or cooler ground (or sea) surface so that condensation ensues in the moist air, with formation of low stratus clouds, often with fog. If the warm air in question is an unstable, turbulent layer of high humidity near the surface, the condensation generally takes place more extensively and the precipitation is heavier than otherwise. This also tends to be true when the motion of the moist air is upward along a sloping cooler surface layer of air or rising ground. Table 3-9 summarizes the visibility for different drizzle intensities.

TABLE 3-9
DRIZZLE INTENSITIES AND VISIBILITY

DRIZZLE INTENSITIES	VISIBILITY (miles)
Heavy	1/4 - 1/2
Moderate	1/2 - 1 1/2
Light	1 1/2 - 6
Trace	6 - 10

- Rain. This type of precipitation falls in showers and consists of drops of liquid water which are generally larger than 0.02 inch in diameter and fall faster than 10 feet per second in still air. Rain must be carefully distinguished from drizzle. While the drops of rain are generally larger than 0.02 inch and those in drizzle always smaller than 0.02 inch, rain drops may, under certain circumstances, have diameters also smaller than 0.02 inch. Such rain drops

are much sparser than drizzle drops. The first rain drops from an advancing canopy of clouds may all have diameters less than 0.02 inch, but then can be distinguished from drizzle by the clouds from which they fall, by not being so numerous, and by not materially reducing the previously existing horizontal visibility as drizzle does. Precipitation of rain may be either fairly continuous or showery, but that of drizzle is rather uniformly continuous and never showery. Thus, rain can occur from shower clouds, such as cumulonimbus or cumulus, but drizzle does not. When the precipitation is rather continuous, a consideration of the clouds is helpful in avoiding confusion between the two phenomena in question. Rain, as distinguished from showers of rain, manifests itself as fairly continuous precipitation of ordinary rain drops from a continuous sheet of cloud. The sky is, as a rule, covered with a layer of real rain clouds (i.e., nonshower clouds such as nimbostratus) formed by progressive lowering from an altostratus system, or with a uniformly gray but relatively high canopy of clouds (altostratus), generally with formless masses of cloud below (scud: fractocumulus or fractostratus), which may even be present in such quantities that the upper clouds are completely hidden. On the other hand, drizzle usually occurs from a continuous dense and low layer of stratified cloud which has formed near the surface, but not from progressive lowering of higher clouds. Rain can be classified according to the intensities in Table 3-10 where light rain is about 0.1 inch/hour and heavy rain about 0.3 inch/hour.

TABLE 3-10

RAIN INTENSITIES AND VISIBILITY

RAIN INTENSITIES	VISIBILITY (miles)
Very Heavy	1/8 - 3/4
Heavy	3/4 - 2 1/2
Moderate	2 1/2 - 6
Light	6 - 20
Very Light	20 - 50

- Snow. This type of precipitation falls in showers and consists of water in the solid state, mainly in the form of branched hexagonal crystals or snowflakes, often mixed with simple ice crystals. Snow ordinarily manifests in the form of single platelike crystals of water in the solid state, or clusters of such crystals which fall more or less continuously from a solid cloud sheet. Because of the mechanical difficulties involved in measuring snow as a rate of weight-accumulation, visibility is used as the criterion for determining the intensity of snowfall. Table 3-11 gives the snow intensities and corresponding visibility.

TABLE 3-11

SNOW INTENSITIES AND VISIBILITY

SNOW INTENSITIES	VISIBILITY (miles)
Heavy	0 - 1/4
Moderate	1/4 - 3/4
Light	3/4 - 2 1/2
Very Light	2 1/2 - 4
Trace	4 - 6

Typical Effects on Visibility by Atmospheric Obstructions

Table 3-12 summarizes the typical effects on visibility by the atmospheric obstructions discussed in the previous section. Typical meteorological ranges are also given in Table 3-13 in values of the scattering coefficient corresponding to some of the typical weather conditions of Table 3-12. In addition, these visibility ranges have been organized into a set of visibility states. The meteorological ranges were obtained by using Equation (2-6), which is as follows:

$$V_M = \frac{3.912}{\beta}$$

where,

V_M = meteorological range or the maximum distance at which large dark or black objects, such as mountains, can be seen against the sky.

TABLE 3-12 *,**,***

TYPICAL EFFECTS OF VISIBILITY BY ATMOSPHERIC OBSTRUCTIONS

VISIBILITY		FOG	HAZE	SMOKE	DUST	BLOWING & DRIFTING SNOW	BLOWING DUST & SAND	SPRAY & BLOWING SPRAY	DRIZZLE	RAIN	SNOW
KILOMETERS	MILES (APPROX.)										
0 - 0.1	0 - 1/16	VH		VH	VH	H	VH				H
0.1 - 0.2	1/16 - 1/8	VH		VH	VH	H	VH				H
0.2 - 0.4	1/8 - 1/4	H		H	H	H	H			VH	H
0.4 - 0.8	1/4 - 1/2	M		H	H	M	H		H	VH	M
0.8 - 1.2	1/2 - 3/4	M		H	H	M	H	H	M	VH	M
1.2 - 1.6	3/4 - 1	L		M	M	L	M	H	M	H	L
1.6 - 2.4	1 - 1 1/2	L	H	M	M	L	M	H	M	H	L
2.4 - 4	1 1/2 - 2 1/2	L	H	L	L	T	L	H	L	H	L
4 - 6.4	2 1/2 - 4	L	M	L	L		L	M	L	M	VL
6.4 - 9.6	4 - 6	T	M	L	L		L	M	L	M	T
9.6 - 16	6 - 10		L	VL	VL		VL	L	T	L	
16 - 32	10 - 20		T	T	T		T	L		L	
32 - 80	20 - 50		T		T		T	VL		VL	
Over 80	Over 50										

NOTE: VH = Very Heavy; H = Heavy; M = Moderate; L = Light; VL = Very Light; T = Trace

* Kraght, Peter E. (1942). Meteorology for Ship and Aircraft Operation, Cornell Maritime Press, N.Y.
** Haynes, B. C. (1947). Techniques of Observing the Weather, John Wiley & Sons, N.Y.
*** McCartney, E. J. (1976). Optics of the Atmosphere, John Wiley & Sons, N.Y.

TABLE 3-13 *,**,***

VISIBILITY STATES AND METEOROLOGICAL RANGES FOR DIFFERENT WEATHER CONDITIONS AND SCATTERING COEFFICIENTS

VISIBILITY STATE	METEOROLOGICAL RANGE (V_M)		TYPICAL WEATHER CONDITIONS	ATTENUATION COEFFICIENT β (km^{-1})
	KILOMETERS	MILES (APPROX.)		
0	0 - 0.05	0 - 1/32	Heavy Snow & Very Heavy Fog	∞ - 78.2
1	0.05 - 0.1	1/32 - 1/16	Very Heavy Fog & Smoke	78.2 - 39.1
2	0.1 - 0.2	1/16 - 1/8	Heavy Blowing & Drifting Snow	39.1 - 19.6
3	0.2 - 0.4	1/8 - 1/4	Heavy Fog & Smoke	19.6 - 9.78
4	0.4 - 0.8	1/4 - 1/2	Heavy Dust & Drizzle	9.78 - 4.89
5	0.8 - 1.2	1/2 - 3/4	Moderate Fog & Snow	4.89 - 3.26
6	1.2 - 1.6	3/4 - 1	Heavy Rain & Spray	3.26 - 2.44
7	1.6 - 2.4	1 - 1 1/2	Moderate Dust & Smoke	2.44 - 1.63
8	2.4 - 4	1 1/2 - 2 1/2	Heavy Haze & Rain	1.63 - 0.98
9	4 - 6.4	2 1/2 - 4	Light Fog & Smoke	0.98 - 0.61
10	6.4 - 9.6	4 - 6	Moderate Haze & Spray	0.61 - 0.41
11	9.6 - 16	6 - 10	Light Haze & Rain	0.41 - 0.24
12	16 - 32	10 - 20	Trace Smoke (Clear)	0.24 - 0.12
13	32 - 80	20 - 50	Trace Haze (Very Clear)	0.12 - 0.05
14	Over 80	Over 50	(Exceptionally Clear)	Below 0.049
15	277	172	(Pure Air)	0.0141

*,**,*** Ibid, page 3-9

EFFECTS OF ATMOSPHERIC OBSTRUCTIONS ON THE ATTENUATION COEFFICIENT *

This section will cover some typical atmospheric obstructions and their effects on the attenuation coefficient. This type of information is useful in assessing the effects of the obstructions on the visual range of objects. Eventually this information will be combined with object contrast to relate all of these parameters to visual range. A typical set of the attenuation coefficient is shown in Figure 3-1 and is particularly important since it shows how the relative attenuation coefficient changes with wavelength and particle size. In general, this figure shows that the attenuation coefficient is relatively constant over the lower wavelengths and decreases significantly at the higher wavelengths. Of course, the larger the particles, the larger the attenuation coefficient.

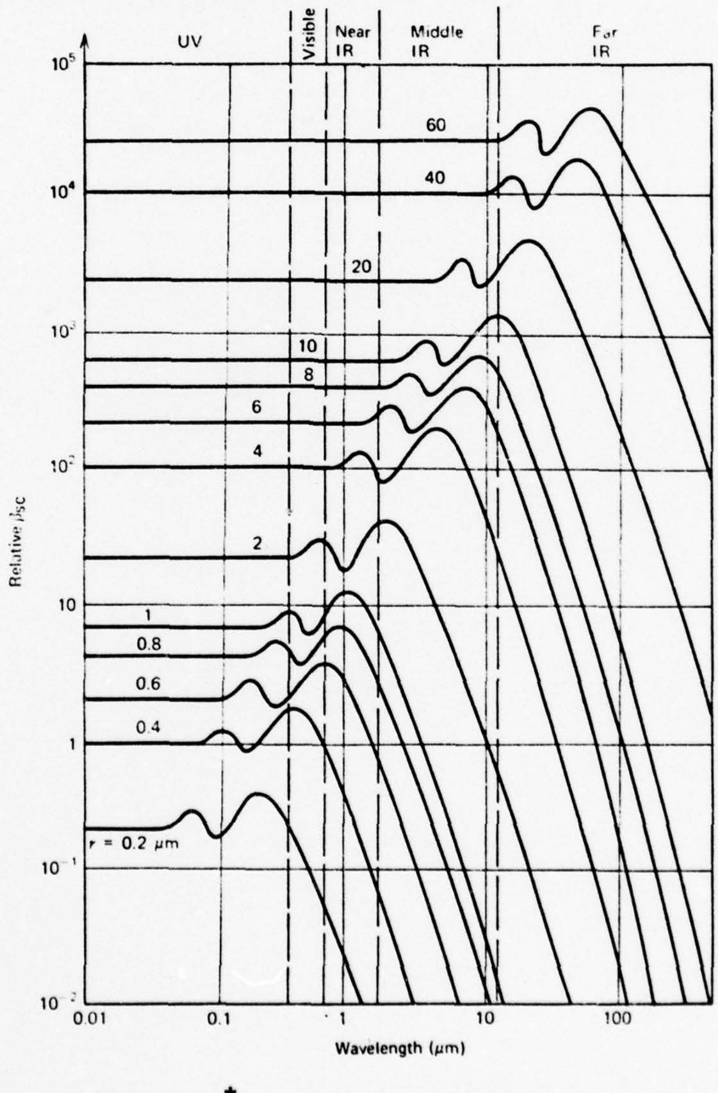


FIGURE 3-1.* RELATIVE VALUES OF TOTAL SCATTERING COEFFICIENTS FOR DIFFERENT WAVELENGTHS AND VARIOUS PARTICLE RADII.

*McCartney, E.J. (1976). Optics of the Atmosphere, John Wiley & Sons, N.Y.

The attenuation coefficients for clouds and rain were computed by Deirmendjian.* The results are summarized in Figure 3-2. A comparison with available measurements of attenuation was made with the addition of Fog (obs), Water vapor (obs) and total estimated (rain -50 + fog + water vapor) data points which agree with the model results. As to attenuation by other types of cloud and precipitation composed of ice particles, snow, and hail, an accurate estimate is not attainable at present since the effects of the irregularity of their shape are not well known and the optical constants have not been completely determined.

Figure 3-2 is a good indicator of the variation of the attenuation coefficient with wavelength and shows the following:

- The attenuation coefficient is relatively constant over the lower wavelengths, especially for rain and cloud C.6. This means that the attenuation coefficient could be determined at the middle IR region of 1-10 microns, and the value would be applicable at the near IR, visible, and ultraviolet wavelengths.

- All the curves show a significant reduction in attenuation coefficient with increased wavelength. This means that measurements at the far IR and radar wavelengths will allow for lower attenuation coefficients and longer visual ranges assuming that object contrast and contrast threshold do not significantly deteriorate.

Figures 3-3 and 3-4 indicate the values of the attenuation coefficients for sensors using the following atmospheric windows (minimum effects on attenuation):

- Visible spectrum - 0.4 to 0.7 microns

- IR spectrum - 3 to 5 microns and 8 to 12 microns

- RF spectrum - 3,200 microns, 8,600 microns, and 30,000 microns

Figure 3-3 indicates the attenuation of optical-frequency radiation. Figures 3-3(a) and 3-3(b) show the attenuation due to haze and fog for selected values of visibility. Since the attenuation due to haze and evolving fog decreases rapidly with increasing wavelength, IR sensors are preferred over visible sensors in hazy weather. For stable fogs and clouds (Figures 3-3(b) and 3-3(c)), IR attenuation is so severe that IR sensors have little advantage over visible sensors. Figure 3-3(d) shows the attenuation due to rain for various precipitation rates where the attenuation is constant from the visible wavelengths through the middle IR wavelengths of about 15 microns since the water particles are much larger than the radiation wavelengths.

* Deirmendjian, D. (1975). Far Infrared and Sub millimeter Attenuation by Clouds and Rain. Rand Corporation, Santa Monica, CA., NTIS AD-A021 947/7sT

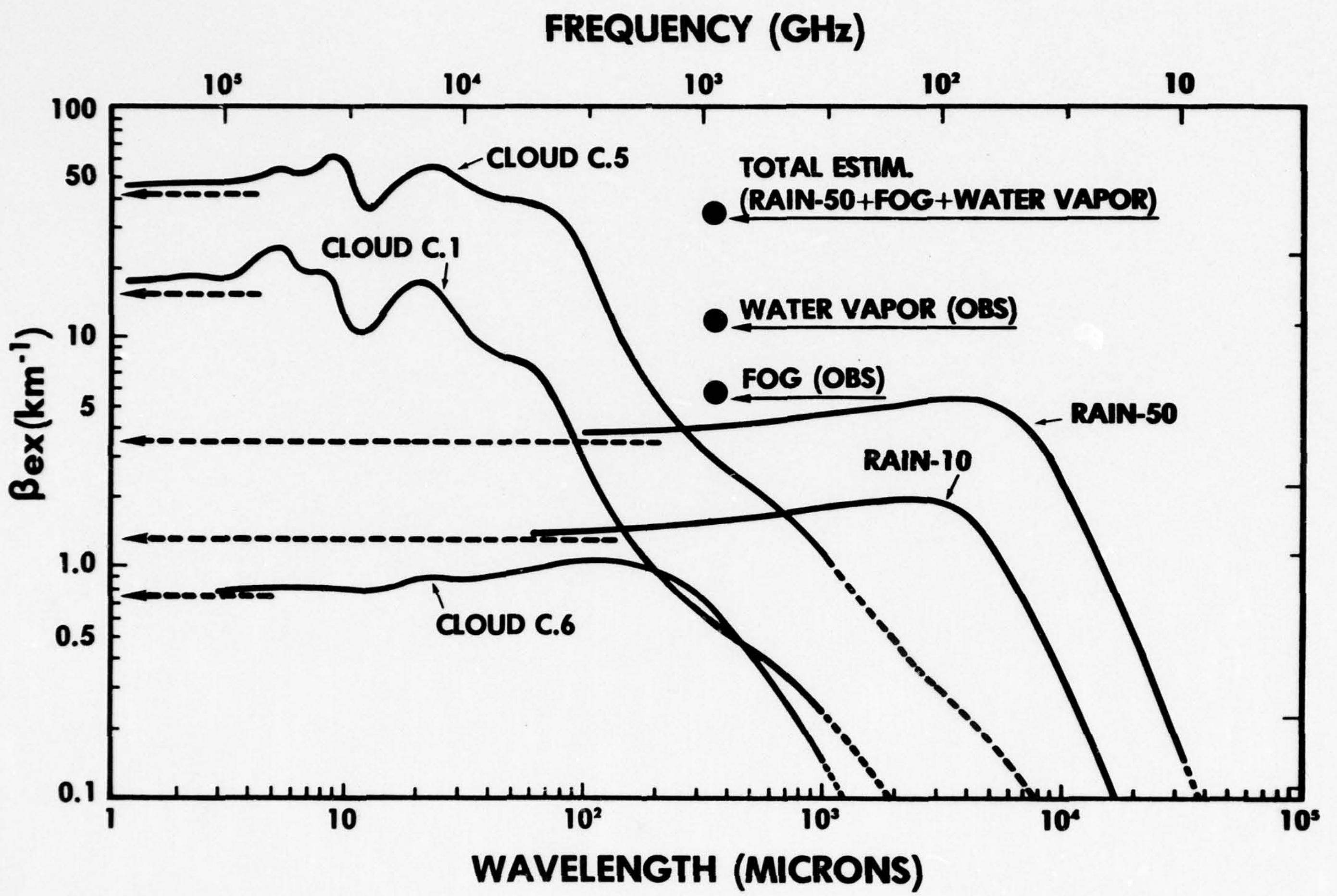


FIGURE 3-2.* THEORETICAL CLOUD- AND RAIN EXTINCTION COEFFICIENTS EXCLUDING WATER VAPOR AND OTHER MOLECULAR ABSORPTION EFFECTS.

Ibid, page 3-12

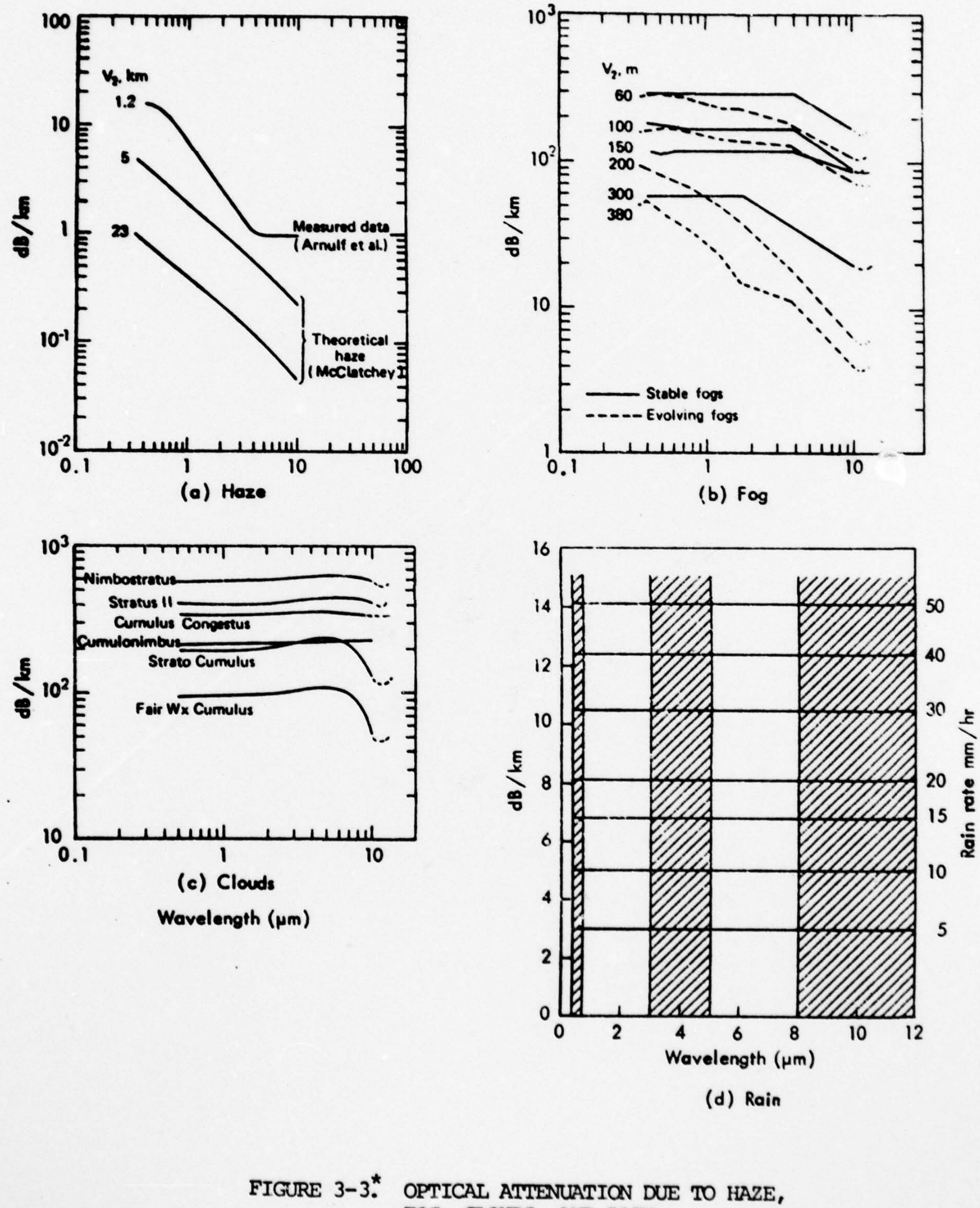


FIGURE 3-3.* OPTICAL ATTENUATION DUE TO HAZE, FOG, CLOUDS, AND RAIN

* Chen, C.C. (1975). Attenuation of Electromagnetic Radiation by Haze, Fog, Clouds, and Rain. Rand Corporation, R-1694-PR, DDC-AD-A011642

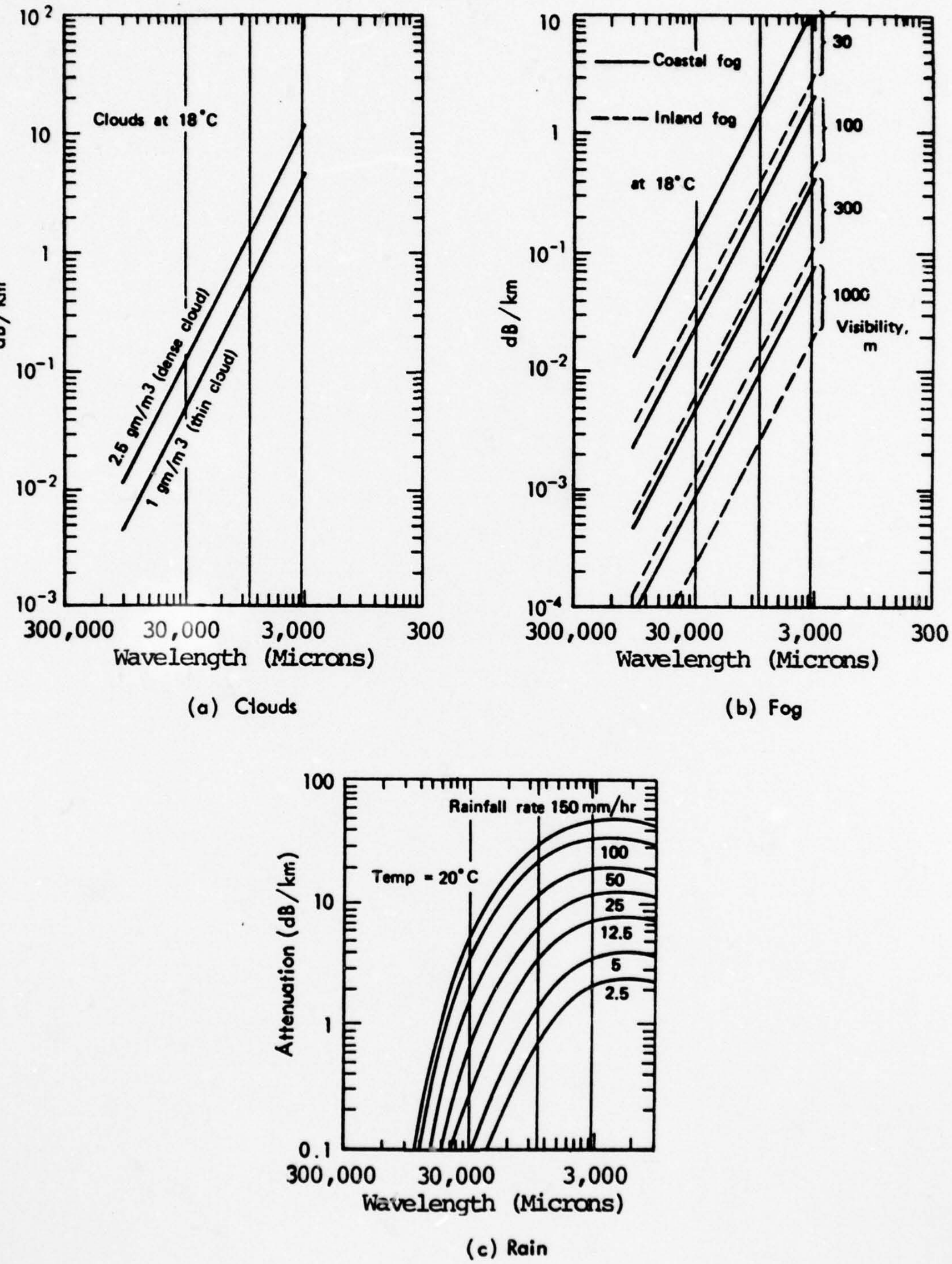


FIGURE 3-4.* RADIO FREQUENCY ATTENUATION DUE TO CLOUDS, FOG, AND RAIN

*Ibid, page 3-14

Figure 3-4 indicates the attenuation of RF frequency radiation due to fog, cloud, and rain. Haze is transparent to RF radiation since haze particles are much smaller than RF radiation wavelenth. Figures 3-4(a) and 3-4(b) show that the attenuation is negligible at 30,000 microns for clouds and fog. The attenuation at 8,600 microns and 3,200 microns depends on the specific conditions and range from negligible to severe. Figure 3-4(c) shows that the attenuation of RF radiation by rain is severe at 8,600 microns and 3,200 microns and is about the same as the attenuation at visible and IR frequencies. It is almost negligible at 30,000 microns even at a precipitation rate of 50 mm/hr.

4. INSTRUMENTS FOR MEASUREMENT OF VISUAL RANGE

Instruments to measure visual range may be separated into two general categories:

- Those instruments that measure contrasts between the visual objects and their background directly. The human eye and telephotometers are contrast measuring instruments.

- Those instruments that measure the attenuation coefficient with the subsequent interpretations of the measurements in terms of visual range according to the mathematical relationships derived earlier in this report. These instruments can be grouped into two specific types:

  -- Those that determine the transmittance of a path of known length using a light source and a telephotometer. Transmissometers are instruments of this type.

  -- Those that measure the scattered light directly by sampling a small volume of air using a source and a receiver. The output of these instruments is assumed to be proportional to the scattering coefficient since the absorption coefficient is assumed to be negligible. Backscatter, side-scatter, and forward-scatter meters are examples of these types of instruments.

TELEPHOTOMETERS

Visual range instruments that measure contrasts (compare brightnesses) are in principle comparison telephotometers. One class of such instruments compares the luminance of a distant source with that of a comparison source in the telephotometer. The other class measures only the relative luminance of two distant sources such as a large dark building and the horizon sky above it. The former class of telephotometer is best suited for visual range measurements at night such as a comparison of the brightness of a distant point source of light with that of an internal point source. Measurement of the relative luminances of distant objects are best suited for daytime use.

Actually, to measure visual range when the target is at a distance, all comparison telephotometers are calibrated according to Equation (2-4) and measure the apparent contrast. For strictly optical instruments, the measurement is a subjective estimate by the viewer as to when the brightness of the target is matched, by insertion of calibrated filters, to that of the horizon sky. Electro-optical instruments eliminate this subjectivity by measurement of the brightness of the target and horizon independently.

TRANSMISSOMETERS *, **

A transmissometer determines the transmittance of a path of known length using a light source and a telephotometer as the receiver. The transmissivity is then computed from the relation,

* Ibid, page 2-15

** Douglas, C. A. (February 1964) Methods of Modifying the Transmissometer System To Permit Its Use During Periods of Very Low Runway Visual Range, NBS Report 8188.

$$T = t_b^{1/b} \tag{4-1}$$

where,

T = transmissivity,

t_b = transmittance over path length b, and

b = path length.

The transmissivity is correlated to the daytime visual range of objects using the following expression,

$$C_t = T^V \tag{4-2}$$

where,

C_t = contrast threshold or the contrast at which an object is just visible against its background, and

V = visual range,

and is correlated to the nighttime visual range of lights using the following expression,

$$E_V = IT^V/V^2 \tag{4-3}$$

where,

E_V = illuminance at range V, and

I = intensity of light source.

It is essential to note that distance enters as an exponential and together with the visual ranges to be determined governs the choice of distance between the light source and receiver of a transmissometer. Two other expressions are useful:

$$C_t = t_b^{V/b} \tag{4-4}$$

is the basis for the calibration of a transmissometer based on the visual range of black objects, and

$$E_V = It_b^{V/b}/V^2 \tag{4-5}$$

is the basis for the calibration of a transmissometer based on the visual range of lights. Transmissometers can be further classified according to the geometrical arrangements of sources and receivers.

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A REPORT ON ATMOSPHERIC OBSTRUCTIONS TO VISIBILITY. VOLUME I. S--ETC(U)
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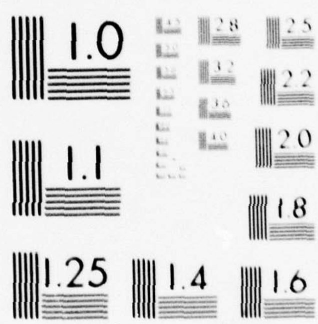


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

- The simplest and most direct arrangement is a straightline one which uses a single source and a single receiver as shown in Figure 4-1. A variation of the straight-line approach uses a single source and two receivers at different distances as shown in Figure 4-2 or a single receiver and two sources positioned at different distances from the receiver. A multiplicity of sources or receivers creates more than one baseline which extends the range of transmissivities which can be determined from the instrument readings.

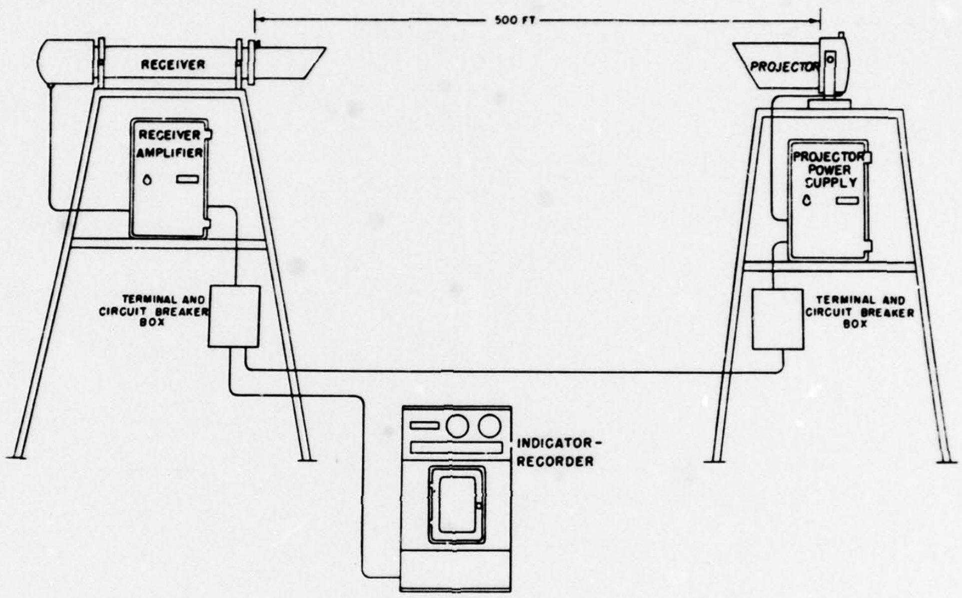


FIGURE 4-1.* TRANSMISSOMETER SET AN/GMQ-10.

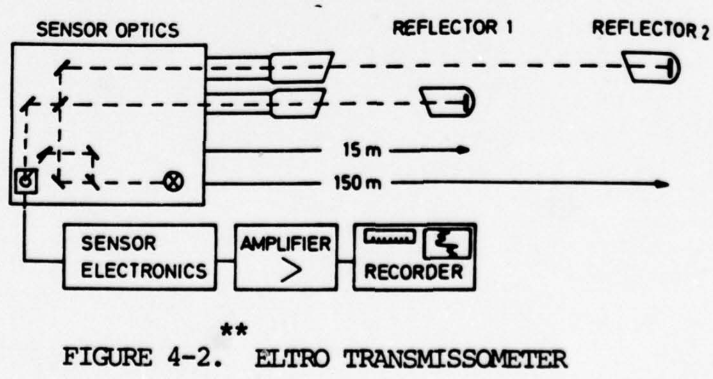


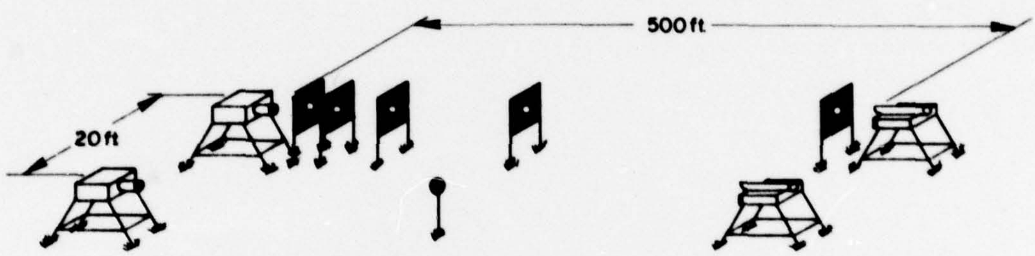
FIGURE 4-2.** ELTRO TRANSMISSOMETER

* National Bureau of Standards, Instruction Book for Transmissometer AN/GMQ-10, NBS Report 2588, Revised January 1955.

** Buchtemann, W. et al, Experimental and Computational Comparison of Different Methods for Determination of Visual Range, AGARD Conference Proceedings, No. 183, October 1975.

- Another arrangement uses folded optics and includes one or more reflectors which fold the light from the source back to the receiver. Since the source and receiver can be located in close proximity to each other when using folded optics, this arrangement is frequently used where long straight-line arrangements are not feasible.

Finally, Figure 4-3 illustrates a typical arrangement of two transmissometers installed on parallel 500 foot baselines 20 feet apart. The details of these transmissometer operations will not be covered in this report because of the availability of a number of reports and handbooks on detailed transmissometer operations.



NOTES: 1. Upper baffled transmissometer measures direct transmittance.
2. Lower transmissometer measures light scattered around disc located midway between the projector and receiver.

FIGURE 4-3. ARRANGEMENTS OF TWO TRANSMISSOMETERS

SCATTERING COEFFICIENT METERS

In many meteorological situations, almost all of the attenuation of a beam of light is due to scattering. When this is true, as with clean fogs, absorption may be neglected completely and the scattering coefficient may be substituted for the attenuation coefficient. Since the concept of obtaining visual range through measurements of scattering assumes that the extinction of a light beam is due solely to scattering, the use of such instruments should be avoided in industrial regions or regions where significant absorption is probable because of the presence of environmental pollution. Scattering coefficient meters are more appropriate for use at sea, for example on aircraft carriers, because absorption is usually negligible over the open sea, the uniformity of the atmosphere minimizes the consequences of the small sample, and the compact design permits use of an instrument of this type under conditions where a transmissometer with the required baseline could not be installed. Scattering coefficient meters may be grouped into three general types:

- Backscatter meters
- Sidescatter meters
- Forwardscatter meters

Backscatter Meters *

A backscatter meter consists of a light source and receiver located nearly adjacent to one another. Both are oriented in the same direction and slightly inclined towards each other, which allows the optical axes to intersect at a known distance. Typically, the light source emits either modulated light or short pulses of light, a portion of which is scattered back toward the receiver. The strength of this backscattered signal is then correlated to atmospheric transmittance through a knowledge of the instrument's calibration. Two simplified arrangements are shown in Figures 4-4 and 4-5. In Figure 4-4, the darkened portion of the diagram represents the volume of air that is capable of scattering light rays back into the receiver. Since the basic components of a backscatter meter are the same as those of a transmissometer, backscatter meters are sometimes erroneously referred to as single-ended transmissometers.

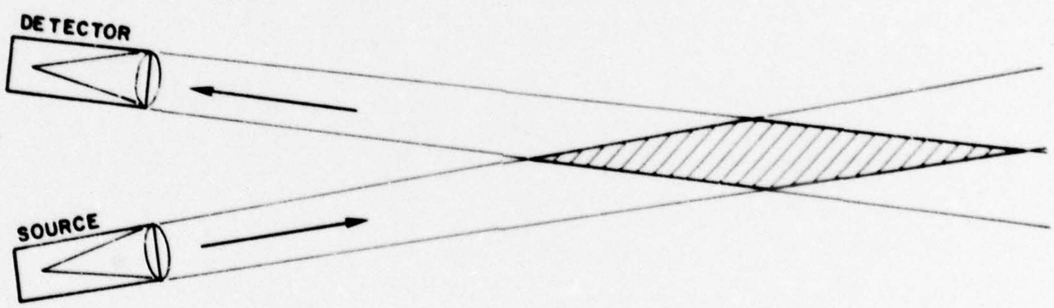


FIGURE 4-4. SIMPLIFIED ARRANGEMENT OF A BACKSCATTER METER

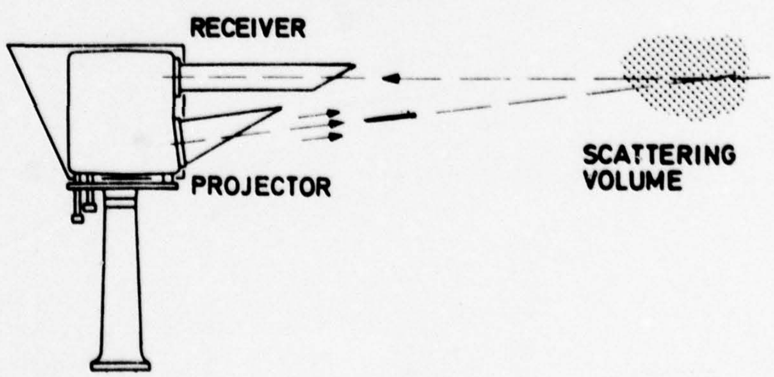


FIGURE 4-5.** DIAGRAM OF A BACKSCATTER VISIBILITY METER (VIDEOGRAPH)

* Vogt, H. (1968). Visibility Measurements Using Backscattered Light. J. Atmos. Sci., 25.
** Ibid, page 4-3 (Buchtemann, W. et al)

The ultimate usefulness of backscatter measurements depends on the existence of some relationship between backscattered light and atmospheric transmittance for actual atmospheric conditions. As previously mentioned, the attenuation of light by the atmosphere is due to both scattering and absorption, with scattering predominating in the visible spectrum. The volume scattering coefficient is defined as the total amount of light scattered by unit volume of air for unit volume of incident illumination. Backscattered light is only a fraction of the total amount of light scattered. The relation between light scattered in a given direction, as is the case with the backscatter meter, and the total scattering coefficient is not constant but depends upon the particle size distribution of the scattering medium. An excellent analysis of this problem is given by Twomey and Howell* who compared white and monochromatic light as sources for measurement of backscatter in determining visibility. They computed the ratio of reflectivity (backscatter signal) to extinction coefficient for the four possible separate combinations of monochromatic and heterochromatic sources incident upon scattering media both homogeneous and heterogeneous in drop-size. These computations showed that increasing the wavelength band of the illuminating light reduces the excursions in this ratio caused by the sharp maxima and minima found in the Mie scattering coefficient and intensity function for a single particle size and wavelength. Thus the use of a broad band source, such as a xenon lamp, is preferable to the use of a monochromatic source, such as a laser.

There have been several field studies of the relation between atmospheric transmissivity and the response of a backscatter meters in a real atmosphere. Measurements were made correlating backscatter measurements with transmittance measurements for a variety of conditions where the meteorological range varied from less than 0.10 mile to more than 40 miles in atmospheres which were free of industrial pollution. The results indicated that visibility can be determined from the backscattered signal with an accuracy of 20% for all visibilities in the ranges studied. This favorable result can be explained theoretically only on the assumption that the sizes of the scattering particles are so irregularly distributed in the atmosphere that their total effect is to produce backscattering almost independent of the type of haze.

Forward Scatter Meters **

In forward scatter meters the receiver accepts light from a source which has been scattered in a near-forward direction as illustrated in Figure 4-6. In addition, it was found that the scattering coefficient in the direction of an angle of about 150° between the axis of the beam and the axis of the receiver was nearly independent of the particle size distribution of the atmosphere. Hence, forward scatter meters are expected to be less sensitive to particle size distribution than are backscatter meters.

* Twomey, S. and Howell, H.B., Relative Merit of White and Monochromatic Light for the Determination of Visibility by Backscattering Measurements. Appl. Opt. 4, 501. (1965).

** Hering, Wayne S., et al (May 1971). Field Test of a Forward Scatter Visibility Meter, Air Force Cambridge Research Labs, Hanscom Field, Mass. DDC-AD-726 995.

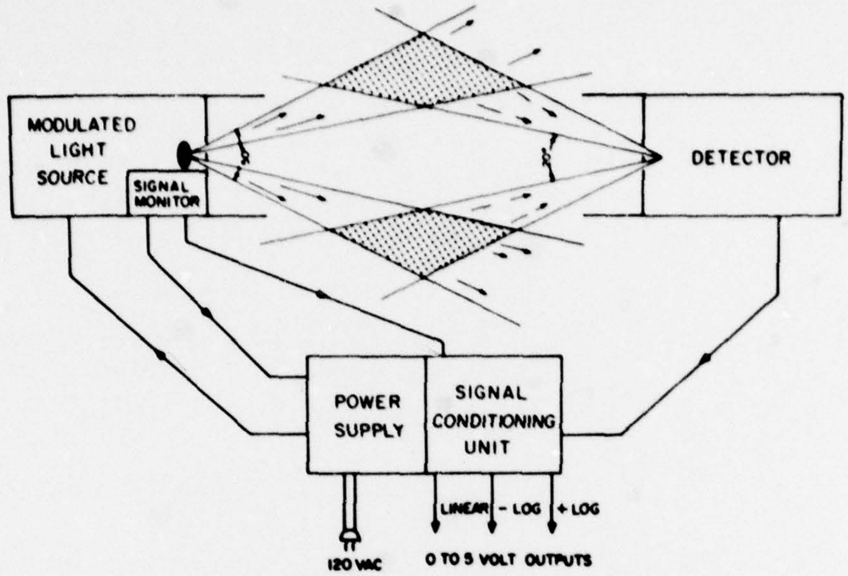


FIGURE 4-6. DIAGRAM OF THE AIR FORCE FORWARD SCATTER METER

The current state-of-the-art is represented by the forward scatter meter developed for the Air Force and shown in Figure 4-6. The light from a halogen-cycle projector lamp is mechanically chopped at 290 Hz before entering an optical system that projects a cone of light, with an inner cone masked out. A photodiode detector is located 120 cm from the projector and receives light from a similar cone-shaped volume. The intersection of the projection and viewing cones forms a sampling volume of 0.05 m^3 where projected light scattered by particulates within this volume at angles between 20 and 50 degrees is accepted by the detector. Synchronous modulation is used in detecting the scattered light. The detected energy is proportional to the extinction coefficient assuming that forward scattering is proportional to total volume scattering, and atmospheric absorption is negligible relative to attenuation by scattering.

This instrument has been thoroughly evaluated through comparisons with both transmissometers and human observers. The feasibility models were tested primarily at the U.S. Naval Radio Station, Cutler, Maine in Augustu 1970. The prototype and production models were tested primarily at three military installations in the fall of 1972 by comparison with transmissometers. Comparisons with visual determinations was also conducted at one of the sites.

Side-Scatter Meters

The principles of the design of side-scatter meters are illustrated by Figure 4-7. The light source is a perfect diffuser and the axis of the photometer is parallel to the plane of the source. Under these circumstances the response of the photometer is proportional to the total scattering coefficient and is independent of the particle size distribution of the aerosols. Ideally, the rays limiting the scattering volume should form an angle of 180°. However, this can only be approximated in practice. Instruments of this type have been used in the study of air pollution, on board ships at sea and an instrument has been designed for airport and fog detector use. Apparently, at present, no instruments of this type have been adopted for operational use.

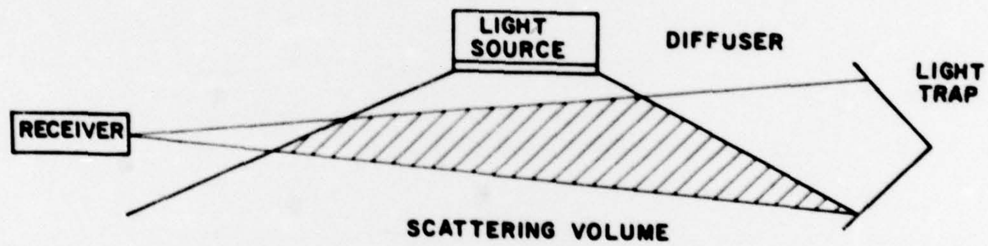


FIGURE 4-7. DIAGRAM OF A SIDESCATTER VISIBILITY METER

OTHER TRANSMITTANCE METERS *, **, ***

In addition to the two general classes of meters described above there are some transmittance meters under development which can be classed as hybrids. These instruments are single-ended devices, intended for use as slant visibility meters, in which light scattered from a small section of the light beam projected by the light source of the instrument is viewed by the receiver. One such instrument uses Raman scattering from the nitrogen in the air induced by a pulsed ultra-violet (nitrogen) laser. The intensity of the Raman scattering from the scattering volume can be computed from the characteristics of the laser source and the characteristics of Raman scattering. Another type is the Lidar instrument where the source is a pulsed laser and the receiver looks out along the beam and is time-gated so that signals are accepted from scattering volumes at different distances. Transmittance is determined from the change in receiver output as a function of distance. A third type instrument is a photoelectric instrument which scans a row of airport runway lights and counts the number visible. No reports of operational use of instruments of this type are available.

* Brown, R. T.,Jr. (May 1967). Backscatter Signature Studies for Horizontal and Slant Range Visibility, Sperry Rand Research Center, Rept.RD-67-24, NTIS AD-659 469.

** Horman, M. H. (1967). Visibility of Light Sources Against a Background of Uniform Luminance, J. Opt. Soc. Am., 57.

*** Evans, W. E. and Collis, R. T. (1970). Meteorological Applications of Lidar, Soc. Photogr. Instr. Eng. 8

5. TECHNIQUES FOR DETERMINING VISIBILITY *

This section will address the practicality of developing techniques, such as charts and graphs, that could be used to determine the visibility due to the effects of atmospheric obstructions on different types of observations and ranging devices. Based on the extensive research performed in this study effort, it can be concluded that it is practical to develop charts and graphs for the purpose given above. Several examples of these charts and graphs will be included in this section to illustrate the technique.

VISIBILITY EQUATIONS

The following equations summarize the visibility on objects and lights and will be used in the charts and graphs:

$V = \frac{1}{\beta} \ln \frac{C_o}{C_t}$	day visibility	(5-1)
$\frac{I}{E} = V^2 e^{-\beta V}$	visibility on lights	(5-2)
$C_t = e^{-\beta V} = T^V$	contrast threshold	(5-3)
$T = e^{-\beta}$	transmissivity	(5-4)
$\beta = -\ln T$	attenuation coefficient	(5-5)
$V_M = \frac{-\ln C_t}{\beta}$	meteorological visibility	(5-6)
$V_M = \frac{3.912}{\beta}$ $(C_t = 0.02)$	meteorological visibility	(5-7)
$T^{V_M} = 0.02$ $(C_t = 0.02)$	meteorological visibility	(5-8)
$T^{V_d} = 0.05$ $(C_t = 0.05)$	day visibility	(5-9)
$\frac{T^{V_N}}{V_N} = 0.0034$	night visibility on lights	(5-10)

In determining the visibility on lights, the following standards for illuminance are generally used:

- E (daylight) = 1000 mile candles
- E (night) = 2 mile candles

* Ibid, page 2-15

TYPICAL CHARTS AND GRAPHS *

This section will cover some typical charts and graphs that could be used to determine the visibility due to the effects of atmospheric obstructions on different types of observations and ranging devices. Tables 3-12 and 3-13 of Section 3 are graphically displayed in Figure 5-1 and summarize the effects of the listed atmospheric obstructions on the meteorological ranges. Figure 5-1 shows the effects of these atmospheric obstructions on the meteorological ranges and essentially displays the solution of Equations 5-6, 5-7, and 5-8. These results will be used in the additional charts and graphs for determining other visibility ranges.

Figures 5-2, 5-3, and 5-4 are typical charts and graphs that illustrate the visibility for a variety of conditions and the effects of these atmospheric obstructions on the different visibilities. These charts and graphs utilized a set of monographs used by the National Bureau of Standards. These figures combine the equations given previously with Figure 5-1 where Equations 5-2, 5-5, 5-8, and 5-10 are solved graphically. The day and night visibility scales are those used in the United States to relate transmissometer measurements to human visibility measurements. These charts and graphs show the following:

- Figure 5-2. Typical chart and graph for short visibility ranges (less than about 1 mile). The ranges of values for the parameters are:

Parameter	Ranges of Values	
	Low	High
I/E	10^{-1}	10^{9}
Range	0.025	1
Transmissivity	10^{-100}	10^{0}
Visibility, Day	0.013	1
Visibility, Night	0.04	2
Meteorological Range	0.017	1
Attenuation Coefficient	0	230

- Figure 5-3. Typical chart and graph for medium visibility ranges (between about 0.1 to 10 miles). The ranges of values for the parameters are:

Parameter	Ranges of Values	
	Low	High
I/E	10^{-1}	10^{9}
Range	0.1	10
Transmissivity	10^{-10}	10^{0}
Visibility, Day	0.13	10
Visibility, Night	0.3	50
Meteorological Range	0.17	20
Attenuation Coefficient	0	23

* Ibid, page 2-15

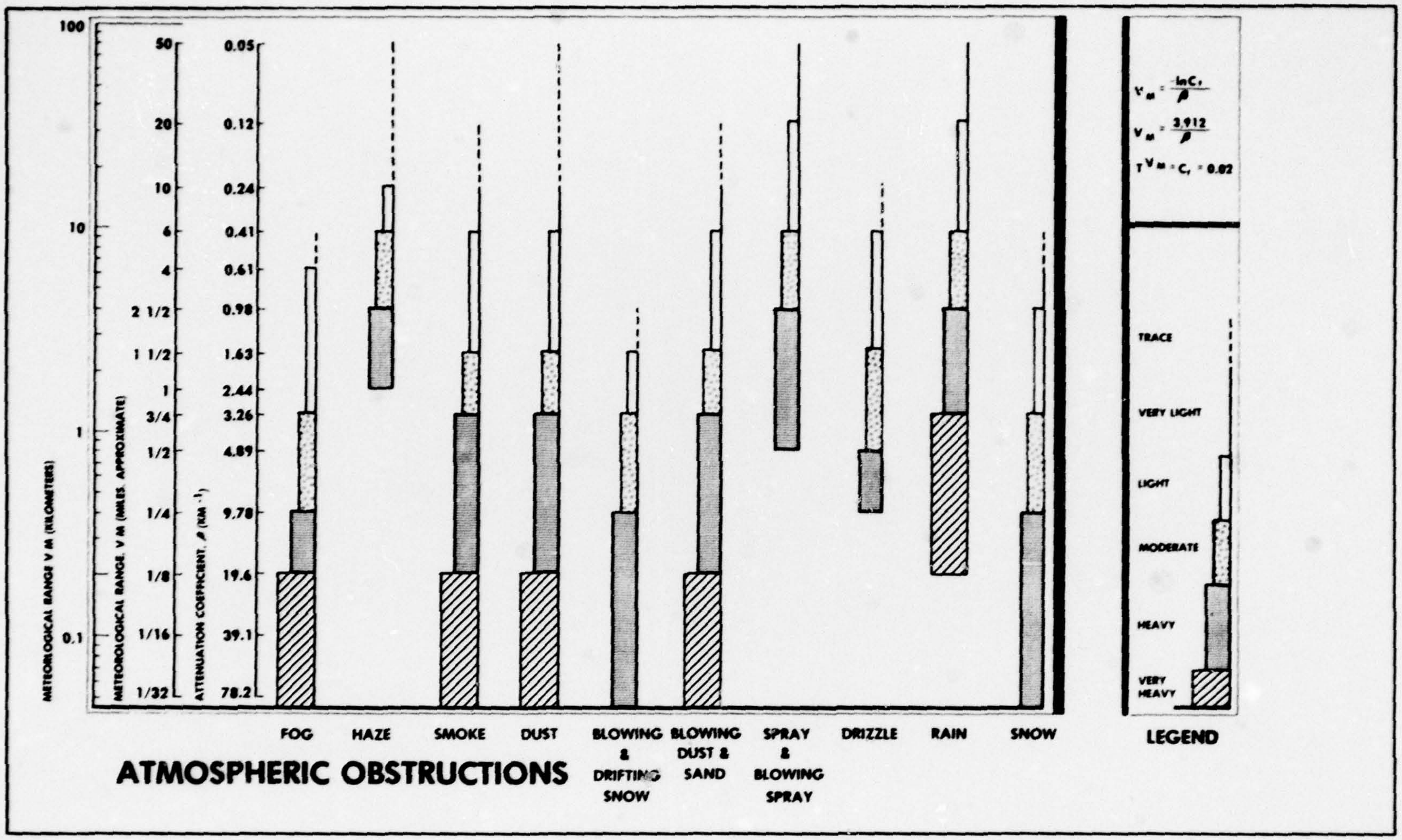


FIGURE 5-1. EFFECTS OF ATMOSPHERIC OBSTRUCTIONS ON METEOROLOGICAL RANGE

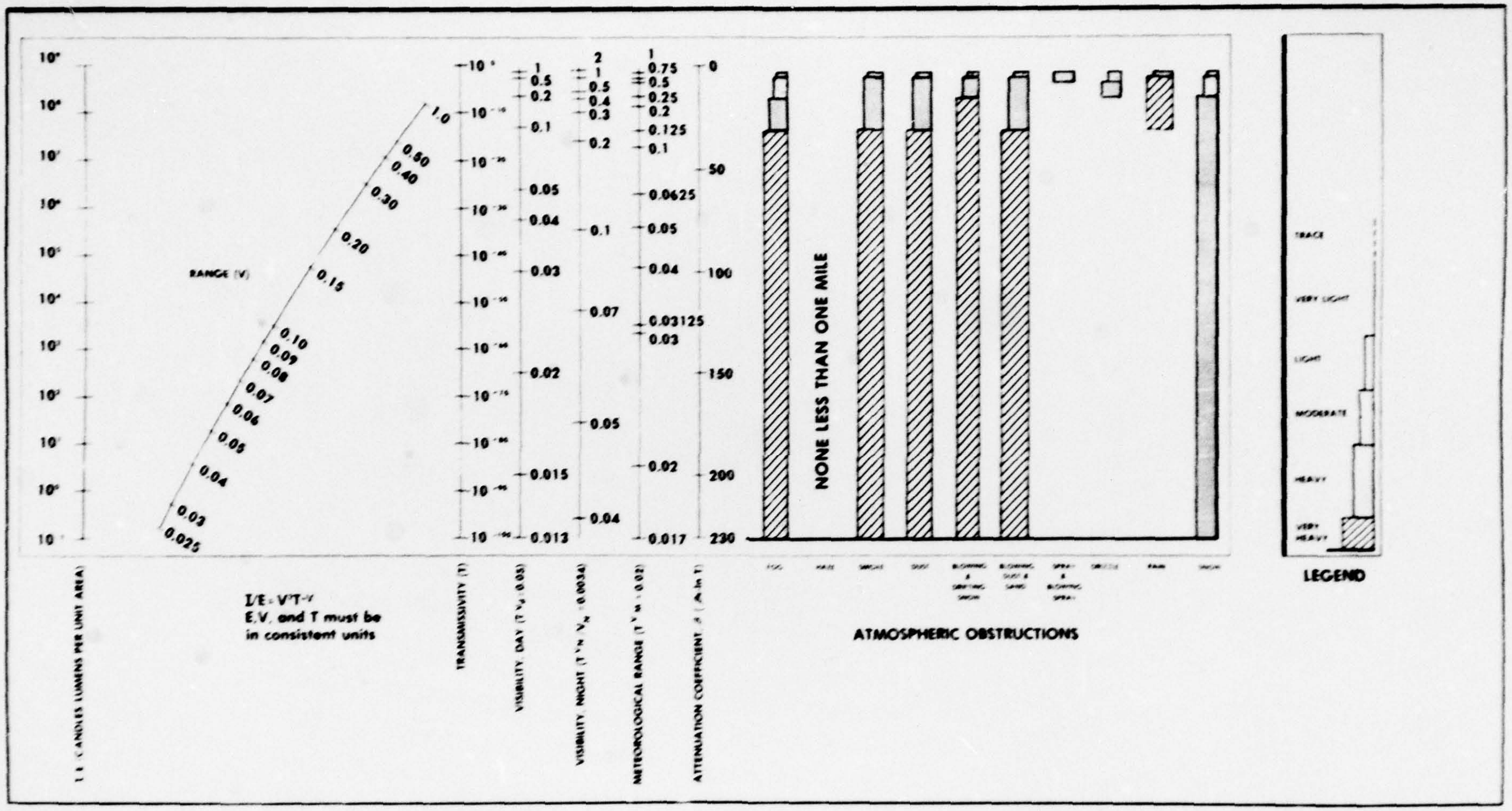


FIGURE 5-2. TYPICAL CHART AND GRAPH FOR SHORT VISIBILITY RANGES AND THE EFFECTS OF ATMOSPHERIC OBSTRUCTIONS

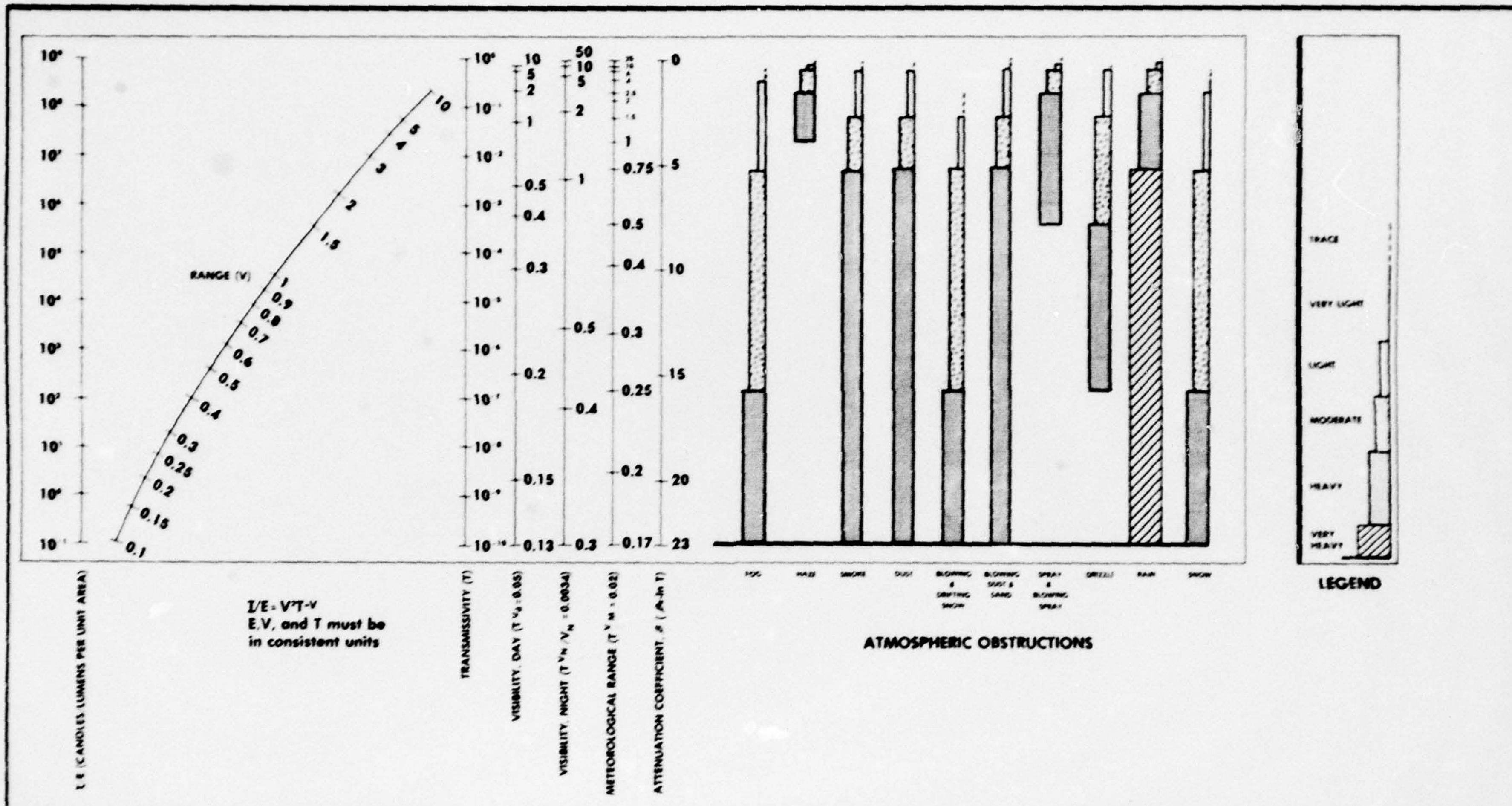


FIGURE 5-3. TYPICAL CHART AND GRAPH FOR SHORT TO MEDIUM VISIBILITY RANGES AND THE EFFECTS OF ATMOSPHERIC OBSTRUCTIONS

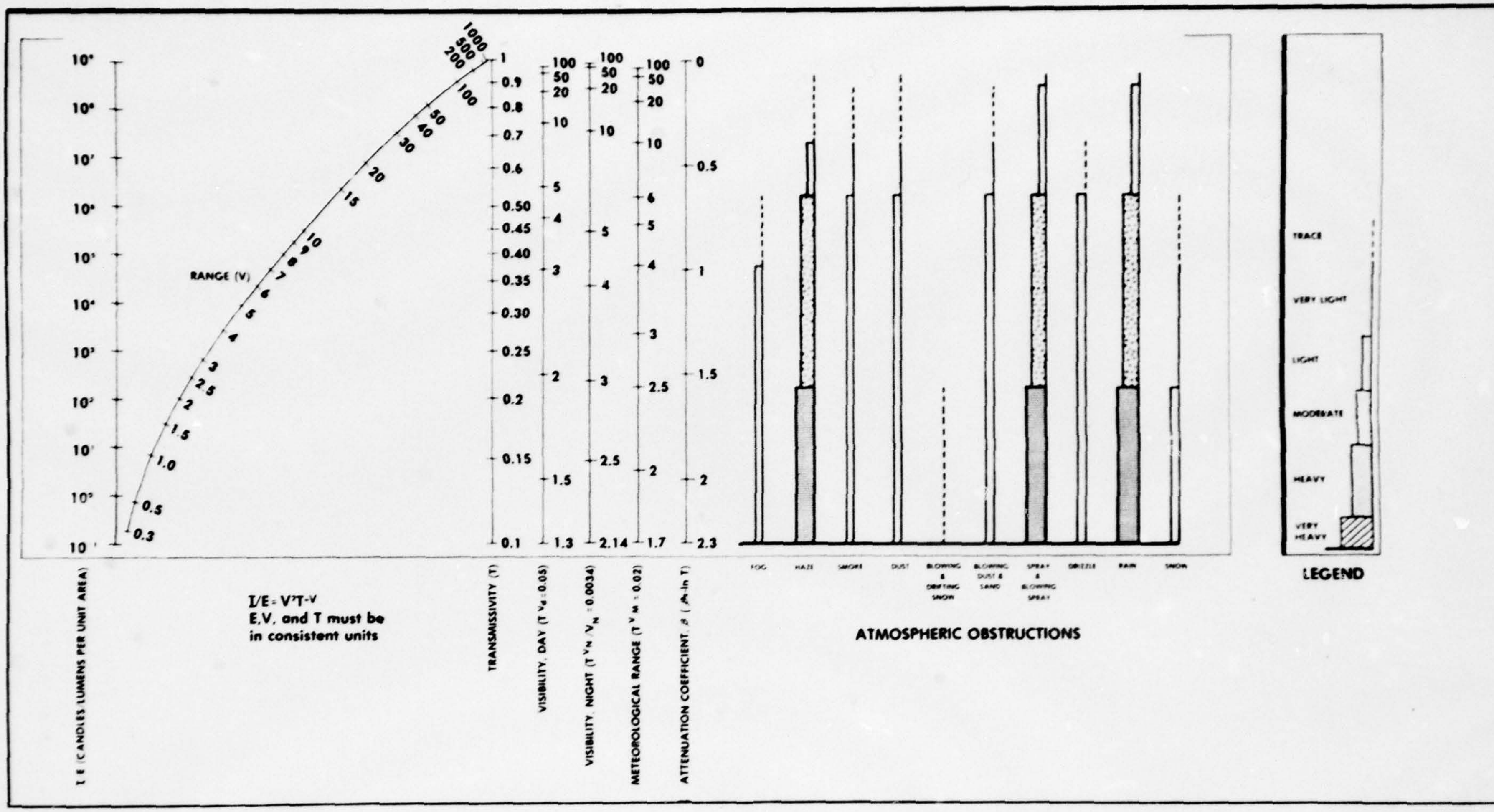


FIGURE 5-4. TYPICAL CHART AND GRAPH FOR MEDIUM TO LONG VISIBILITY RANGES AND THE EFFECTS OF ATMOSPHERIC OBSTRUCTIONS

- Figure 5-4. Typical chart and graph for long visibility ranges (between about 0.3 to 1000 miles). The ranges of values for the parameters are:

Parameter	Ranges of Values Low	High
I/E	10^{-1}	10^{9}
Range	0.3	1000
Transmissivity	0.1	1
Visibility, Day	1.3	100
Visibility, Night	2.14	100
Meteorological Range	1.7	100
Attenuation Coefficient	0	2.3

EXAMPLES

Several examples will be exercised to show how these charts and graphs could be used.

Example 1

At what range can a light with an intensity of 100,000 candelas be seen in daylight when the day visibility is one mile? Using Figure 5-3, from 1 on the VISIBILITY, DAY scale draw a horizontal line to the TRANSMISSIVITY scale which reads T = 0.05. Now I/E = 100,000/1000 = 100 (since E = 1000 candelas for daylight) and from 100 on the I/E scale draw a line to T = 0.05. Read the RANGE (V) scale = 1.34 miles. The types of meteorological obstructions that would cause this condition correspond to an attenuation coefficient of about 3/mile and include:

- Light fog, blowing and drifting snow, and rain.
- Moderate smoke, dust, blowing dust and sand, and drizzle.
- Heavy haze, spray and blowing spray, and rain.

Example 2

At what range can a light with an intensity of 100,000 candelas be seen at night when the night visibility is 1 mile? Using Figure 5-3, from 1 on the VISIBILITY, NIGHT scale, draw a horizontal line to the TRANSMISSIVITY scale which reads T = 0.0034. Now I/E = 100,000/2 = 50,000 (since E = 2 candelas for night) and from 50,000 on the I/E scale draw a line to T = 0.0034. Read the RANGE (V) scale = 1.71 miles. The types of meteorological obstructions that would cause this condition correspond to an attenuation coefficient of about 6/mile and include:

- Moderate fog, blowing and drifting snow, drizzle, and snow.
- Heavy smoke, dust, blowing dust and sand, and spray and blowing spray.
- Very heavy rain.

Example 3

Under moderate fog conditions, what are the ranges on the lights of examples 1 and 2 and what are the ranges for the other visibility parameters? Using Figure 5-3, the parameter values are read off the scales corresponding to the moderate fog bar graph and are:

Parameter	Range of Values Low	Range of Values High
Attenuation Coefficient	5.2	15.7
Meteorological Range	0.25	0.75
Visibility, Night	0.42	1.08
Visibility, Day	0.19	0.58
Transmissivity	1.5×10^{-7}	5×10^{-3}
Range, Daylight	0.4	0.9
Range, Night	0.7	1.8

OTHER TYPES OF CHARTS AND GRAPHS

In addition to Figures 5-1 through 5-4, there are other charts and graphs that can be generated to determine the effects of atmospheric obstructions on visibility including outside the visible spectrum. These include scattergrams such as the one shown in Figure 5-5 that can relate the visibilities between observers and instruments given a set of measurements.

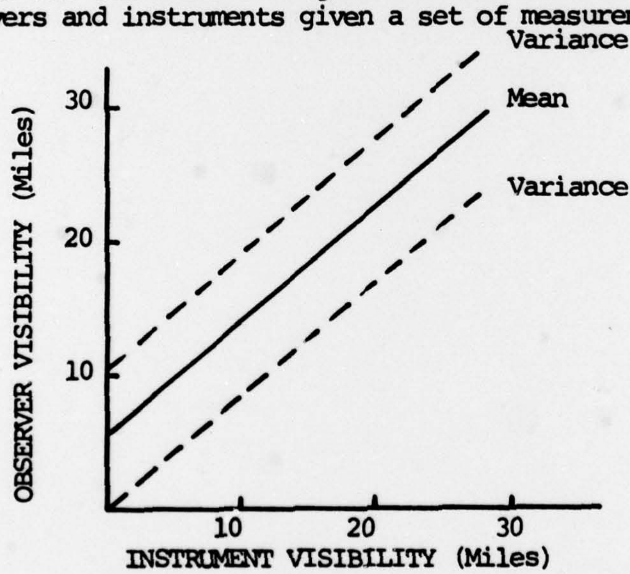


FIGURE 5-5.* TYPICAL SCATTERGRAM RELATING VISIBILITIES

The generation of charts and graphs relating ranges for observation in the visible spectrum to those outside the visible spectrum are possible only if a viable set of relationships can be determined and relied on, such as those in Figures 3-1 through 3-4 of Section 3. The potential of determining these methods was outside the scope of this study effort but should be addressed in subsequent study efforts.

* Ibid, page 2-17

6. LIST OF DEFINITIONS

Absorption - removal of flux from a given beam of light.

Absorption Coefficient (β_{ab}) - measure of the flux absorbed as light passes through a lamina thickness perpendicular to the line of sight.

Attenuation - removal of light from the viewing path and addition of light into the viewing path.

Attenuation Coefficient (β) - measure of the attenuation. Usually the sum of the absorption and scattering coefficients.

Brightness (β) - same as luminance. It is the visual sensation.

Contrast (C_o) - difference in brightness between various parts of the viewed field.

Contrast Threshold (C_t) - minimum contrast at which an object is visible against its background under stated conditions.

Diffraction - modification which light undergoes in passing by opaque bodies or through narrow slits or being reflected from surfaces where the light rays appear to be deflected.

Dipole - pair of equal and opposite electric charges or magnetic poles of opposite sign separated by a small distance.

Electromagnetic Spectrum - entire range of wavelengths or frequencies of electromagnetic radiation extending from gamma rays to the longest radio waves and including visible light.

Extinction Coefficient - same as attenuation coefficient.

Flux (Luminous Flux) - time rate of flow of luminous energy (light).

Illuminance (E) - luminous flux per unit area.

Illuminance Threshold - minimum illuminance at the eye required to make a light source visible.

Intensity (Luminous Intensity) (I) - luminous flux per unit solid angle.

Interference (of light) - mutual effect on meeting of two light waves of the same type so that such light waves produce lines, bands, or fringes either alternately light and dark or variously colored.

Ionized - conversion wholly or partly into ions.

Isotropic - exhibiting properties (such as velocity of light transmission) with the same values when measured along axes in all directions.

Light - in the strict sense, light is that part of the electromagnetic spectrum that is capable of causing a visual sensation directly. However, in common practice it also applies to radiation that contains some ultraviolet and infrared radiation in addition to visible radiation.

Luminance (L) - photometric brightness or luminous intensity of any surface in a given direction per unit of projected area of the surface as viewed from that direction.

Luminance Contrast Threshold - minimum luminance contrast at which an object is visible against its background under stated conditions.

Meteorological Range (V_M) - maximum distance at which large dark or black objects, such as mountains and buildings, can be seen against the sky.

Mile Candle - unit of measure of illuminance and is the illuminance which would be produced by a source having an intensity of one candela at a distance of one mile in a perfectly transmitting atmosphere.

Modulation - process of varying the amplitude, frequency, or phase of a carrier or signal.

Orthicon - camera tube similar to, but more sensitive than, an iconoscope (electron gun and photoemissive mosaic screen, each cell of which produces a charge proportional to the varying light intensity of the image focused on the screen) where the charges are scanned by a low-velocity beam.

Photoelectric - various electrical effects due to the interaction of radiation (light and others) with matter.

Photometric - relating to the measurement of the intensity of light, usually by a photometer, within the context of carefully specified spectral and geometric constraints.

Photon - quantum of radiant energy.

Polarization - cause radiation (light and others) to vibrate in a definite pattern.

Quantum - one of the very small increments or parcels into which many forms of energy are subdivided.

Quantum Jump - abrupt transition from one discrete energy state to another.

Radiometric - discipline concerned with measuring the attributes of light within the context of carefully specified spectral and geometric constraints.

Reflectance - fraction of the total radiant flux incident upon a surface that is reflected and that varies according to the wavelength distribution of the incident radiation.

Refraction - deflection from a straight path undergone by a light ray or energy wave in passing obliquely from one medium (such as air) into another (such as glass) in which its velocity is different.

Runway Visual Range - value normally determined by instruments located alongside and about 14 feet higher than the centerline of the runway and calibrated with reference to the sighting of high intensity runway lights or the visual contrast of other targets - whichever yields the greater visual range.

Scattering - addition of flux into a given light beam.

Scattering Coefficient (β_{sc}) - measure of the flux scattered as light passes through a lamina thickness.

Threshold - value of a physical stimulus that permits an object to be seen a specific percentage of the time or at a specific accuracy level.

Transmission - passage of radiation through a medium without changes in the frequency of the monochromatic components of which the radiation is composed.

Transmissivity - transmittance for a unit distance within a light transmitting medium.

Transmissometer - instrument for measuring the regular transmittance of the atmosphere between two points in space.

Transmittance - ratio of the transmitted luminous flux to the incident flux.

Unpolarized - random pattern of vibrations.

Visibility (Meteorological Visibility) - greatest distance at which selected objects can be seen and identified.

Visual Range (V) - maximum distance, usually horizontal, at which a given object or light is visible under particular conditions of atmospheric transmission and background luminance.

Wavelength - the distance in the line of advance of a wave from any one point to the next point of corresponding phase. For light traveling in a vacuum, wavelength is the velocity of light divided by the frequency.

The following definitions are related to the intensity terms used in Section 3 of this report. These terms correspond to the type of obstruction to visibility encountered.

Trace - very clear conditions usually resulting in very long visibility ranges.

Very Light - clear conditions usually resulting in long visibility ranges.

Light - better than moderate conditions resulting in better than moderate visibility ranges.

Moderate - moderate conditions usually resulting in moderate visibility ranges.

Heavy - poor conditions usually resulting in short visibility ranges.

Very Heavy - very poor conditions usually resulting in very short visibility ranges.

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